Beam Monitoring for Detector Protection at CDF

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Fermilab
8/24/06

How Does Beam Effect the Detector?

Chronic Radiation Damage

- surface damage to silicon electronics
- bulk damage to silicon sensor and electronics

Acute Radiation Damage

- damage or failure of detector system due to categories below

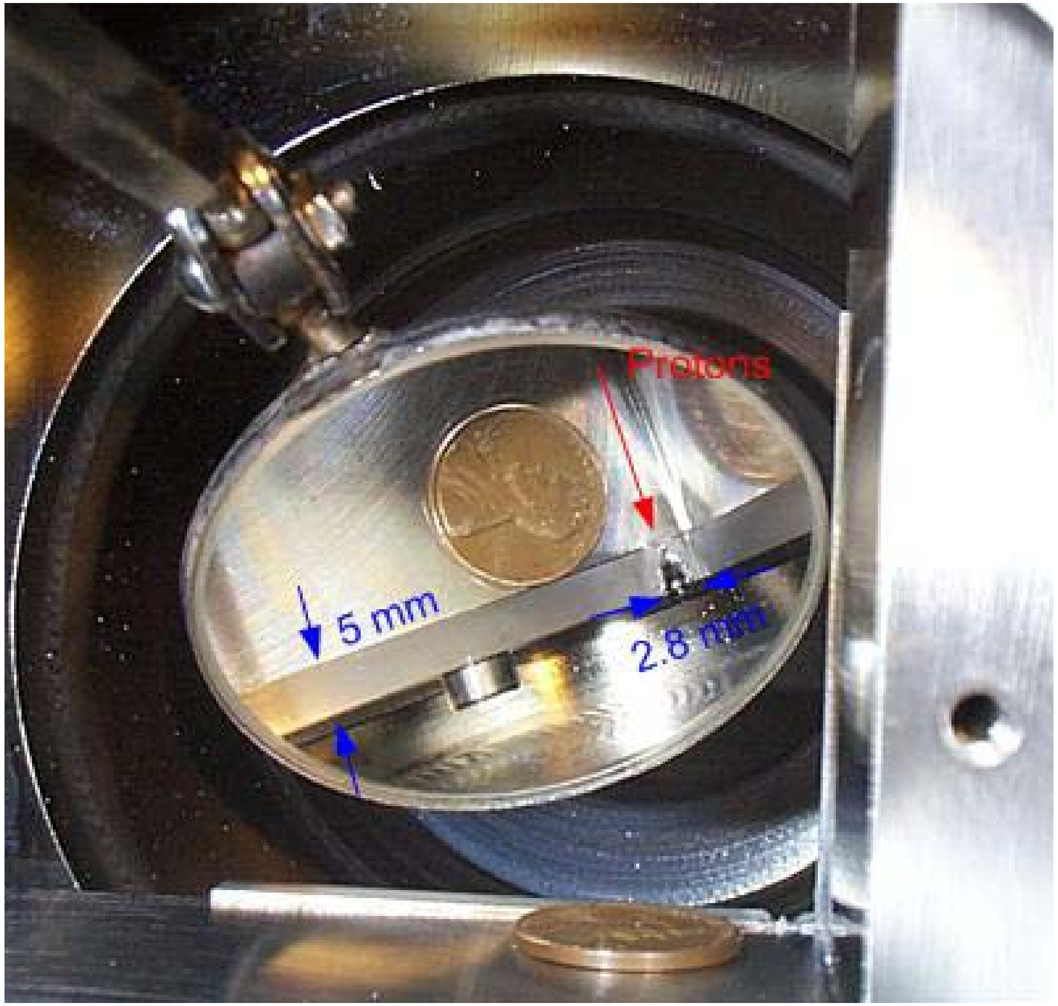
Single Event Effects (SEE) in Electronics

- corruption of instrumentation
- state changes
- data corruption

Catastrophic Failures

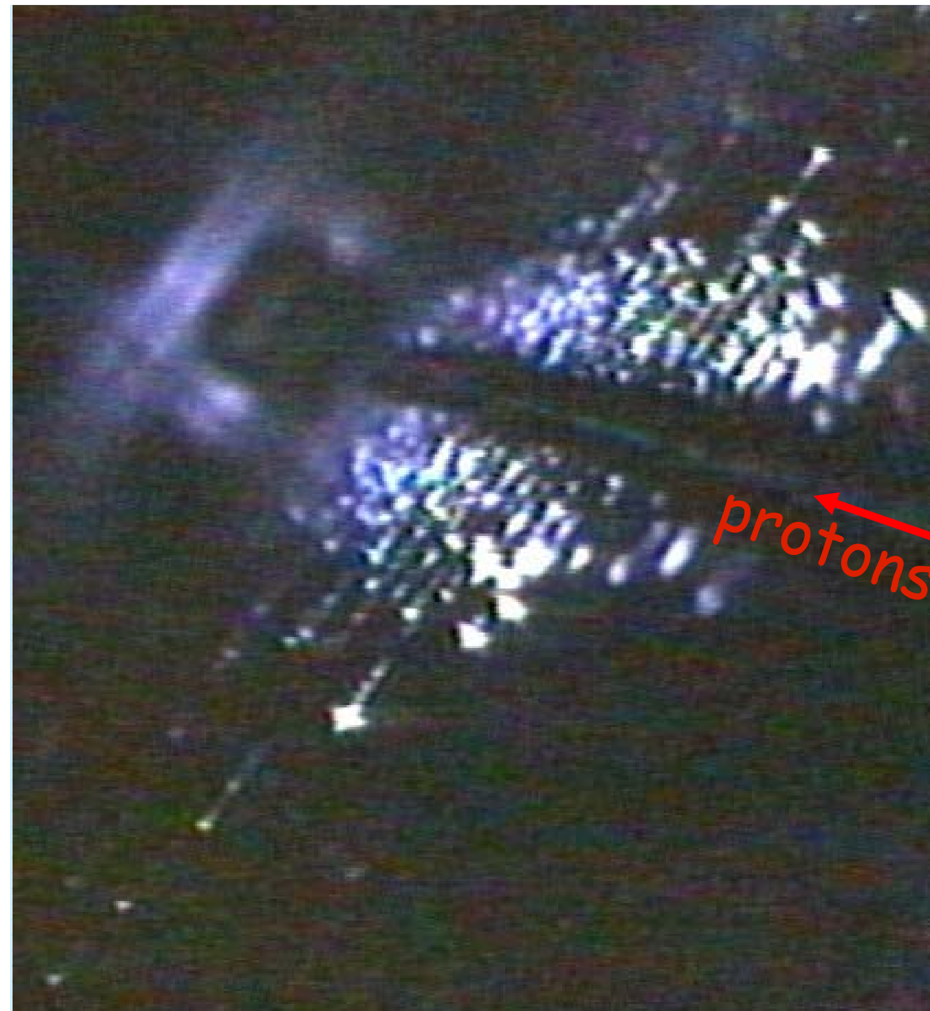
- functional destruction of some portion of the system
- physical destruction of some portion of the system

Corrector Magnet Quench 12/5/03



D49 “target” hit by proton beam
(5mm tungsten plate)

D03 collimator hit by proton beam
(1.5 m steel)



What Problems are Expected?

What can go wrong will and at the worst possible moment. -- Murphy

High radiation dose rates

- high luminosity
- high beam losses

Failure to control beam

- RF
- apertures
- accelerator tune
- dampers
- vacuum
- abort

Any beam control device has the potential to fail and result in loss of beam control.

Understanding the Problem

If you know the enemy and you know yourself, you need not fear the result of a hundred battles -- Sun-Tzu (ca.400 BC)

Lack of beam/accelerator control is the enemy!

Know the enemy:

- Understand the accelerator
- Understand accelerator instrumentation
- Add instrumentation: gain intelligence on accelerator performance

Know yourself:

- Know your detector
- Understand your instrumentation

Main Control Room is an ally!

Talk Organization

I. Introduction to the Tevatron and CDF
   - accelerator
   - CDF detector
   - beam instrumentation

II. Experience
   - what we’ve done right
   - what we’ve done wrong

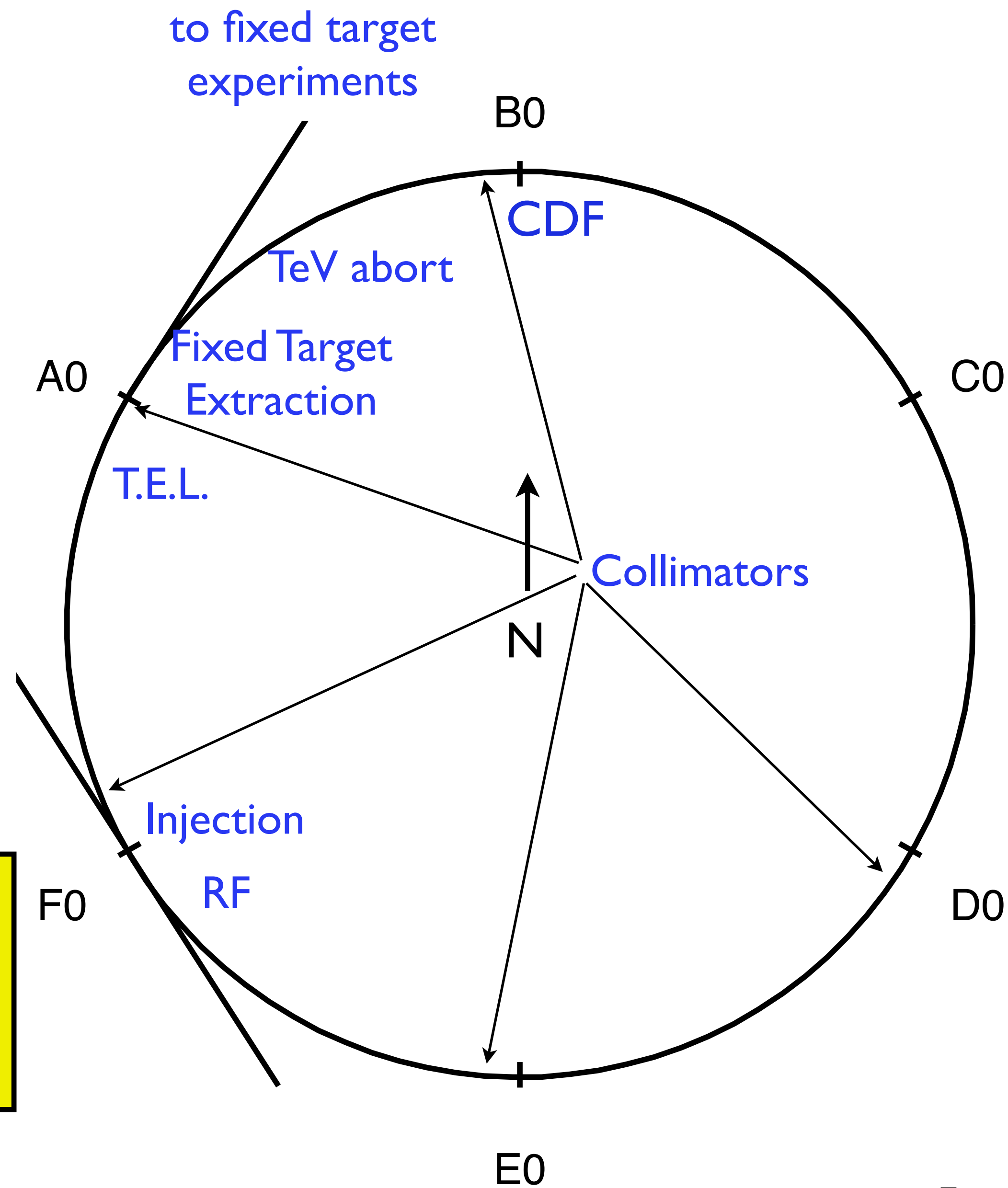
Disclaimers:

- Much of the information presented here is summarized from other, much more detailed sources.
- Some of the work in this talk is in progress, I attempt to represents our best understanding.
- Some crucial instrumentation omitted from this talk for brevity.

Accelerator Map

- 6 sectors (A-F)
- 5 houses/sector (0-4)
  - Accelerator access
  - Tevatron infrastructure (power, water, cryogenics, etc.)
- Abort near A0
  - devices near CDF are aperture restrictions downstream of abort.

** Devices far from CDF affect beam quality



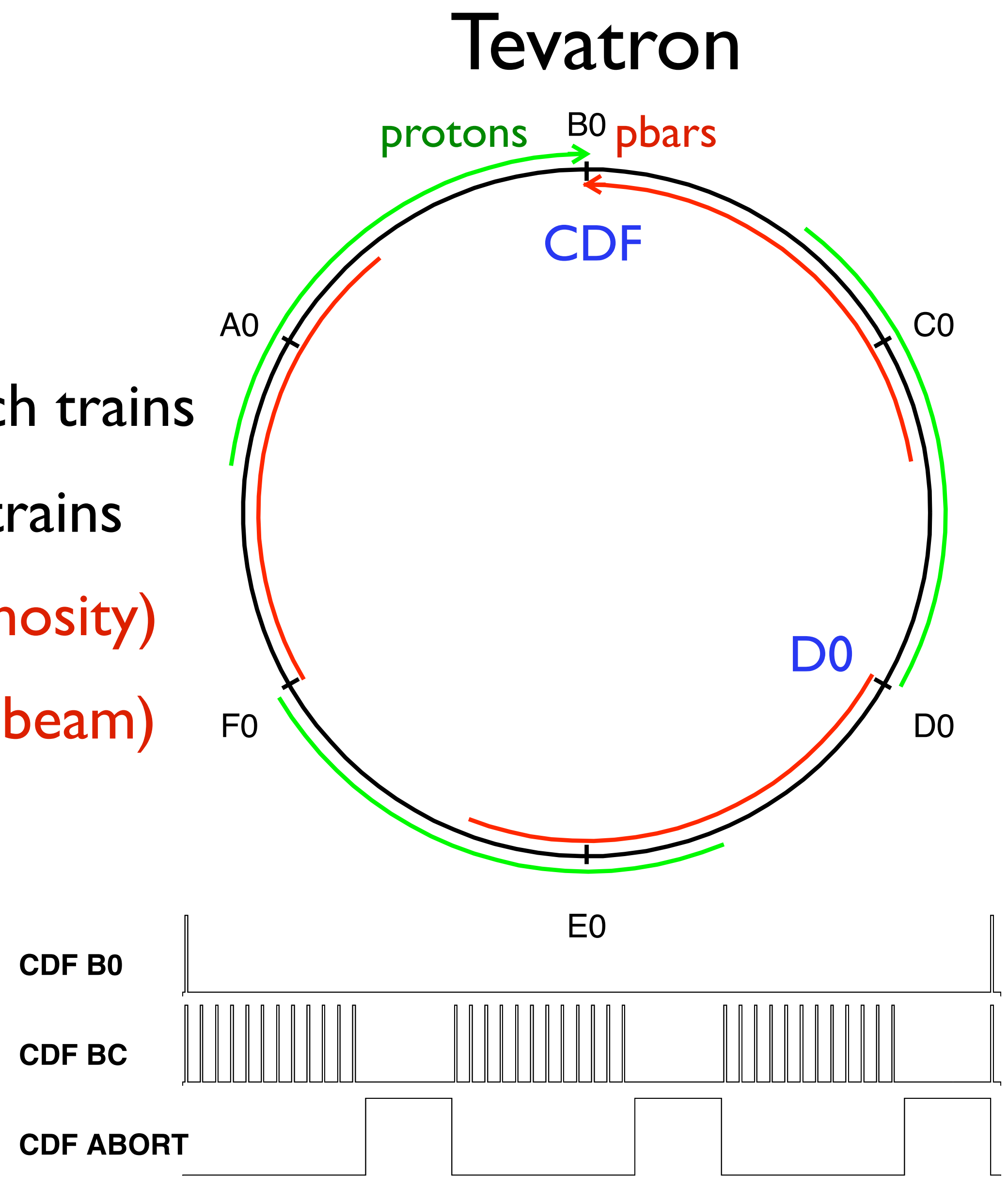
Beam Structure

- 36 1ns bunches in 3x12 bunch trains
- ~2μs space between bunch trains

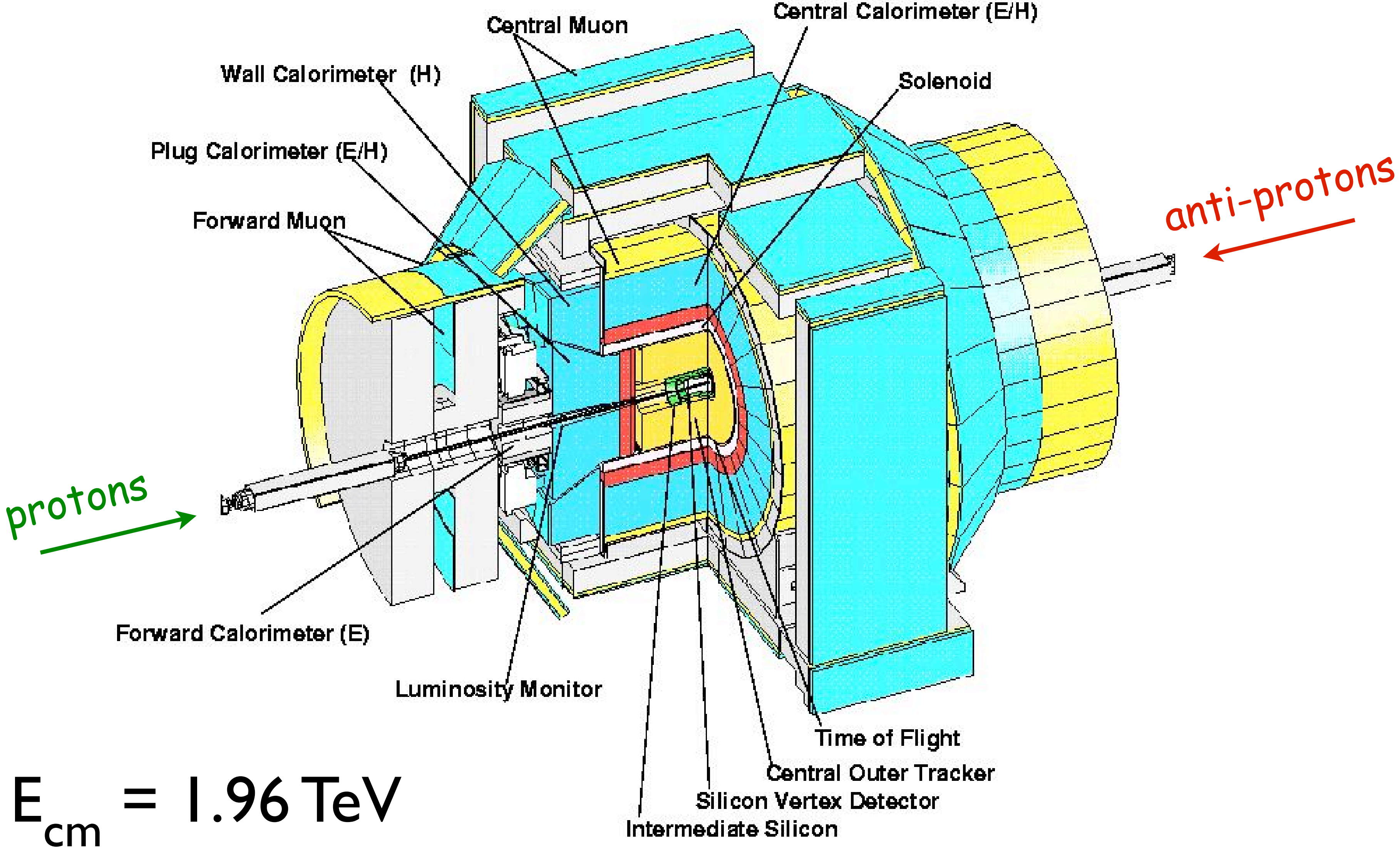
* Monitor collision rates (luminosity)

* Monitor losses (in time with beam)

* Monitor beam in abort gaps

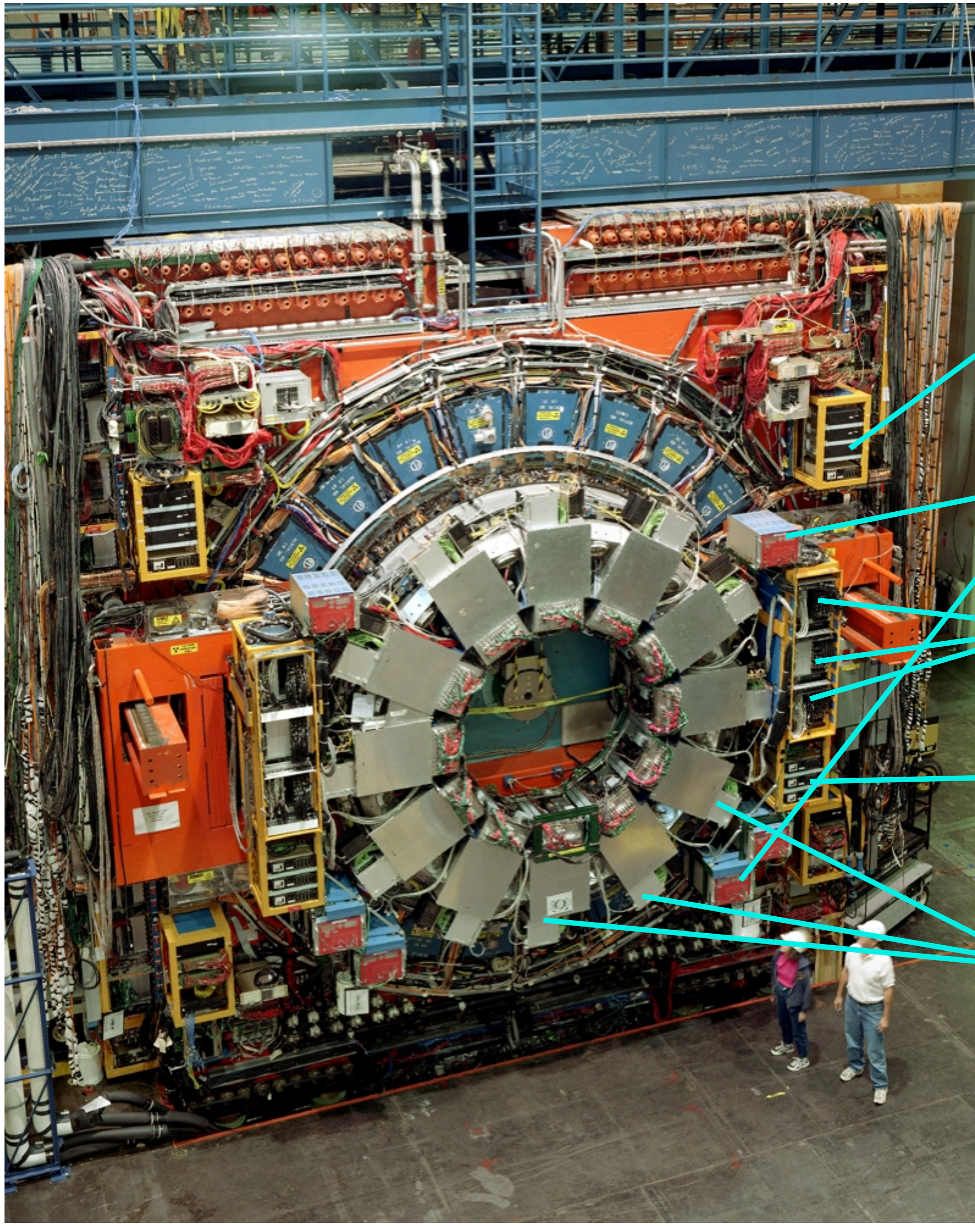


CDF-II Detector (G-rated)



$E_{cm} = 1.96$ TeV

CDF Detector (Adults Only)



Readout, control and support electronics located on the detector:

5kW custom low voltage (LV) switching power supplies

Commercial remotely operated high voltage (HV) switching power supplies

Custom digitizing and readout electronics 9U VME crate (FPGA based)

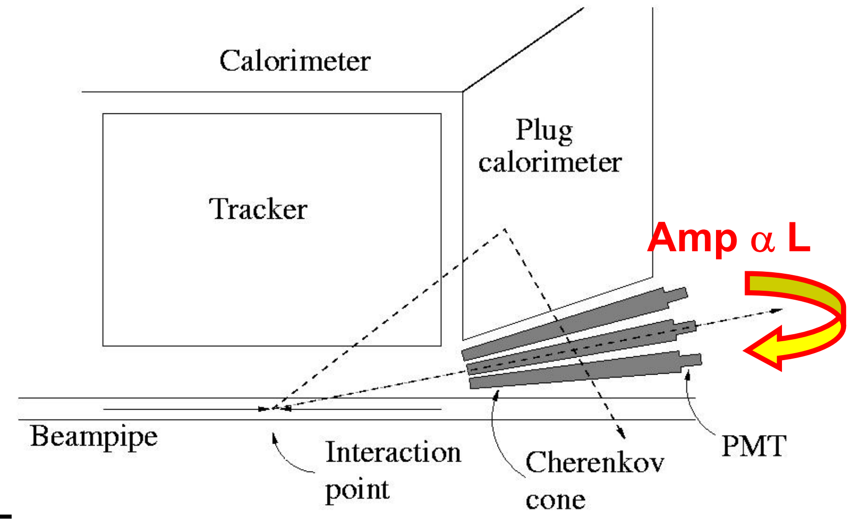
1 kW commercial low voltage (LV) linear power supplies.

Custom digitizing and readout electronics 6U VME crate (FPGA based)

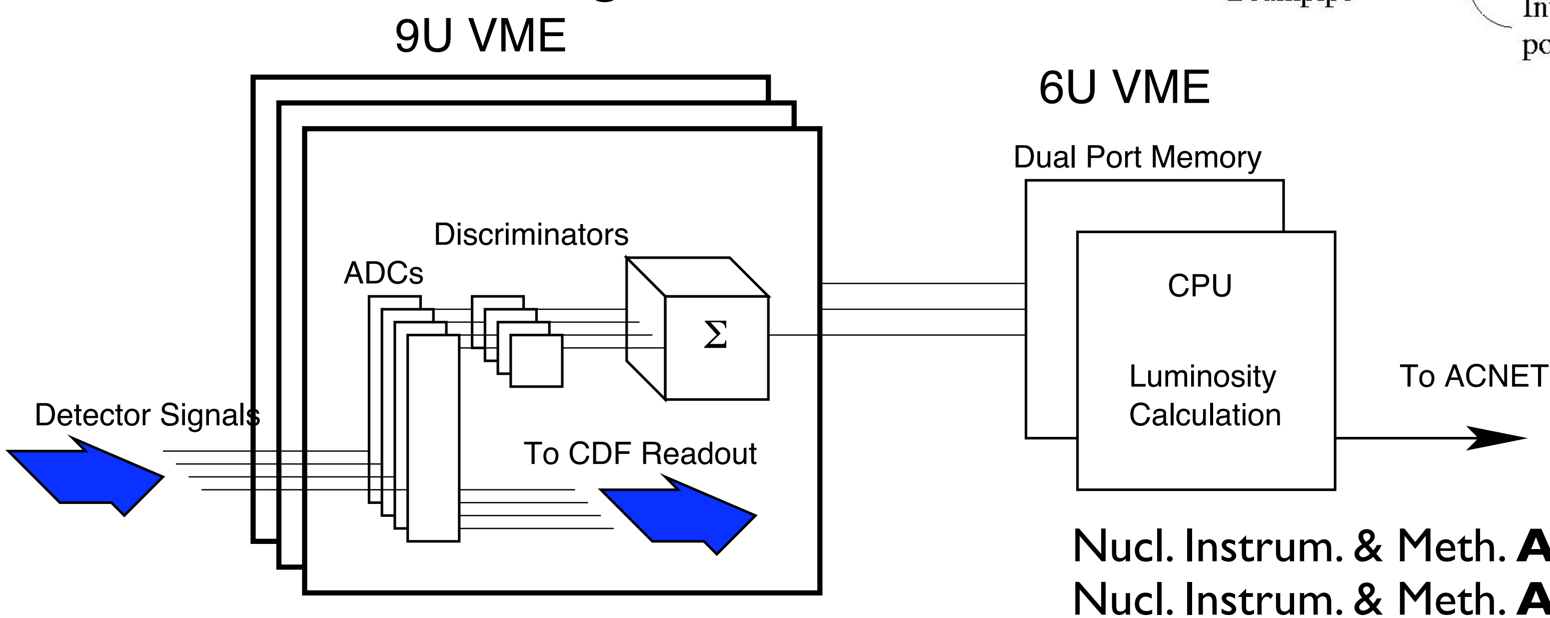
Luminosity Measurement

Cherenkov Luminosity Counters (CLC):

- 96 counters (48 each side of IP)
- sensitive to collisions
- timing and pulse height information
- realtime monitor to accelerator



Functional Diagram of Electronics



Nucl. Instrum. & Meth. **A441** (366-373) 2000.
Nucl. Instrum. & Meth. **A461** (540-544) 2001.

Measuring Beam Losses/Halo

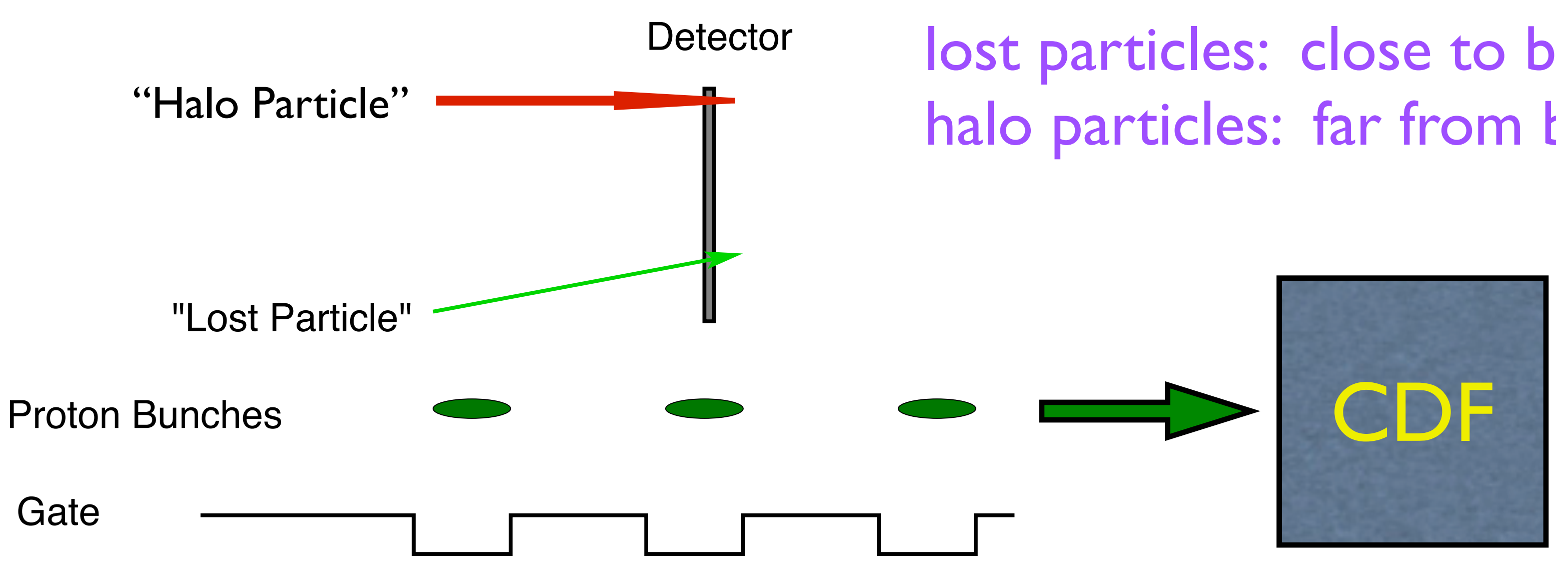
Beam Losses all calculated in the same fashion

- Detector signal in coincidence with beam passing the detector plane.
- ACNET variables differ by detector/gating method.
- Gate on bunches and abort gaps.

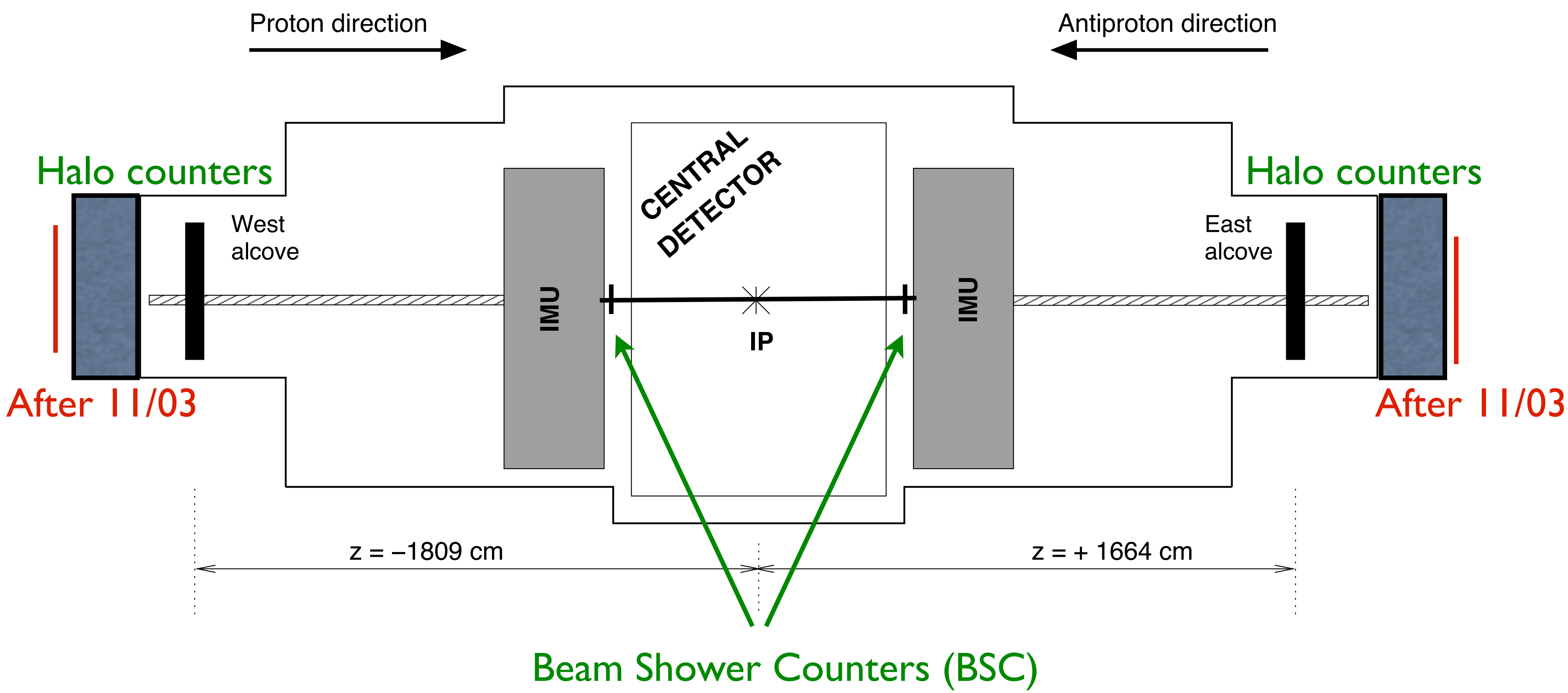
Definitions:

lost particles: close to beam

halo particles: far from beam



Beam Monitors



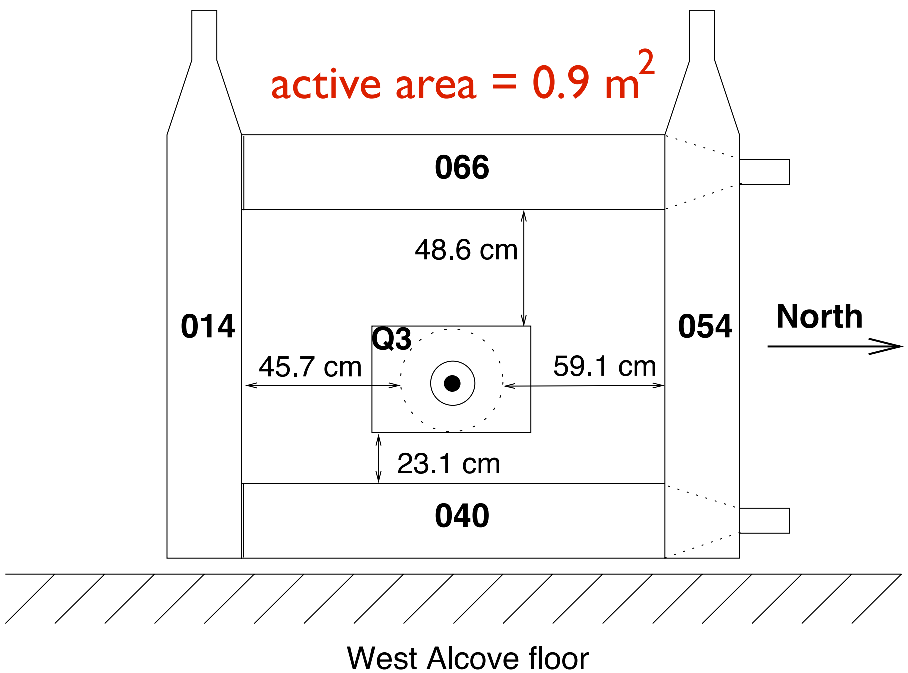
BSC counters: monitor beam losses and abort gap

Halo counters: monitor beam halo and abort gap

Detectors

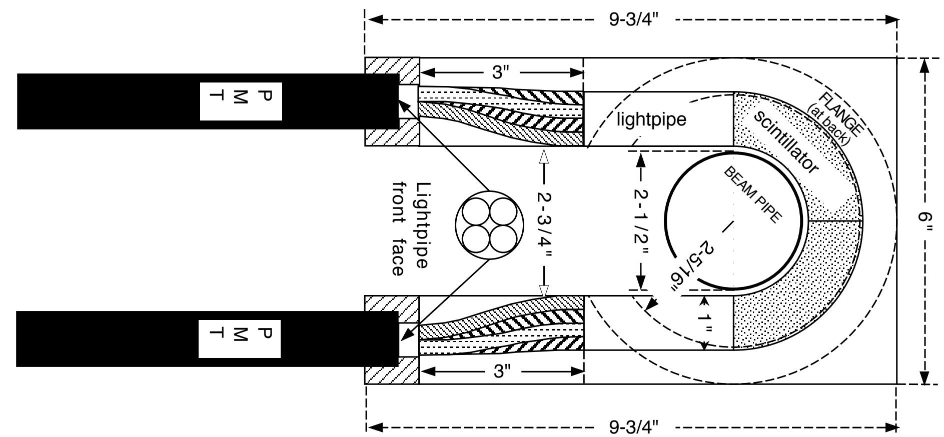
Halo Counters

active area = 0.9 m^2



Beam Shower Counters

active area = 77 cm^2

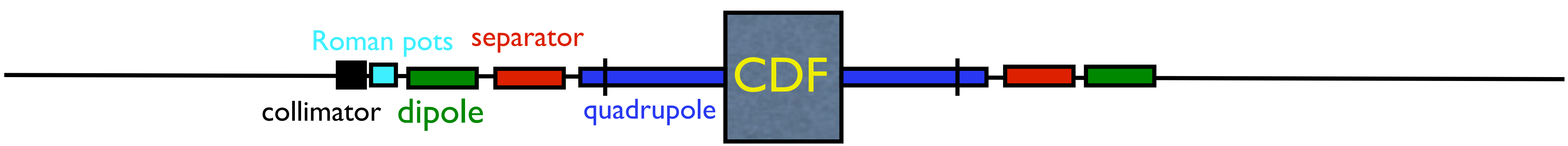


ACNET variables:

B0PHSM: beam halo
B0PBSM: abort gap losses
B0PAGC: 2/4 coincidence abort gap losses

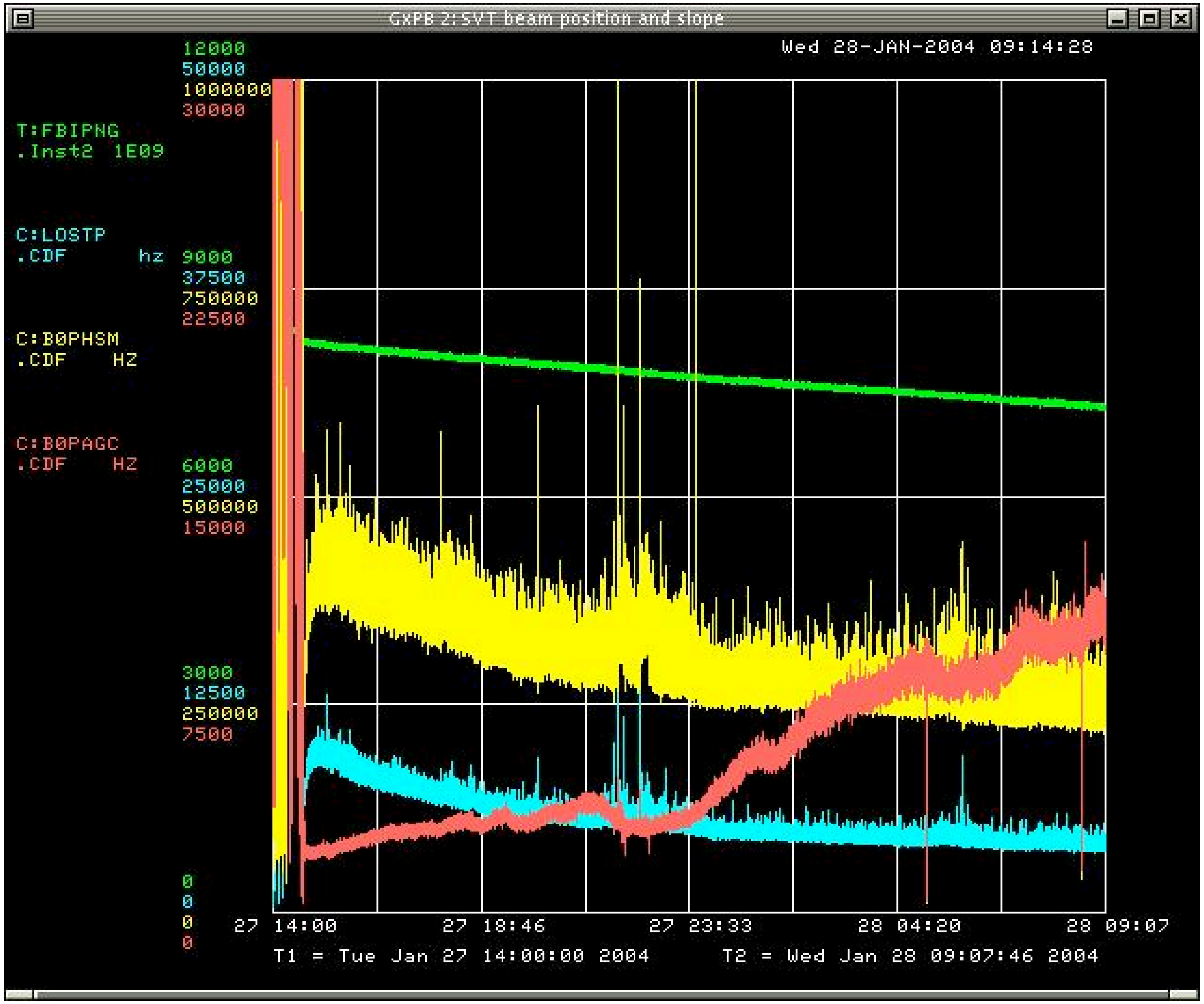
B0PLOS: proton losses (digital)
LOSTP: proton losses (analog)
B0MSC3: abort gap losses (E*W coincidence)

Beam Halo Counters



Monitor Experience

Typical Good Store (2004)



proton beam current

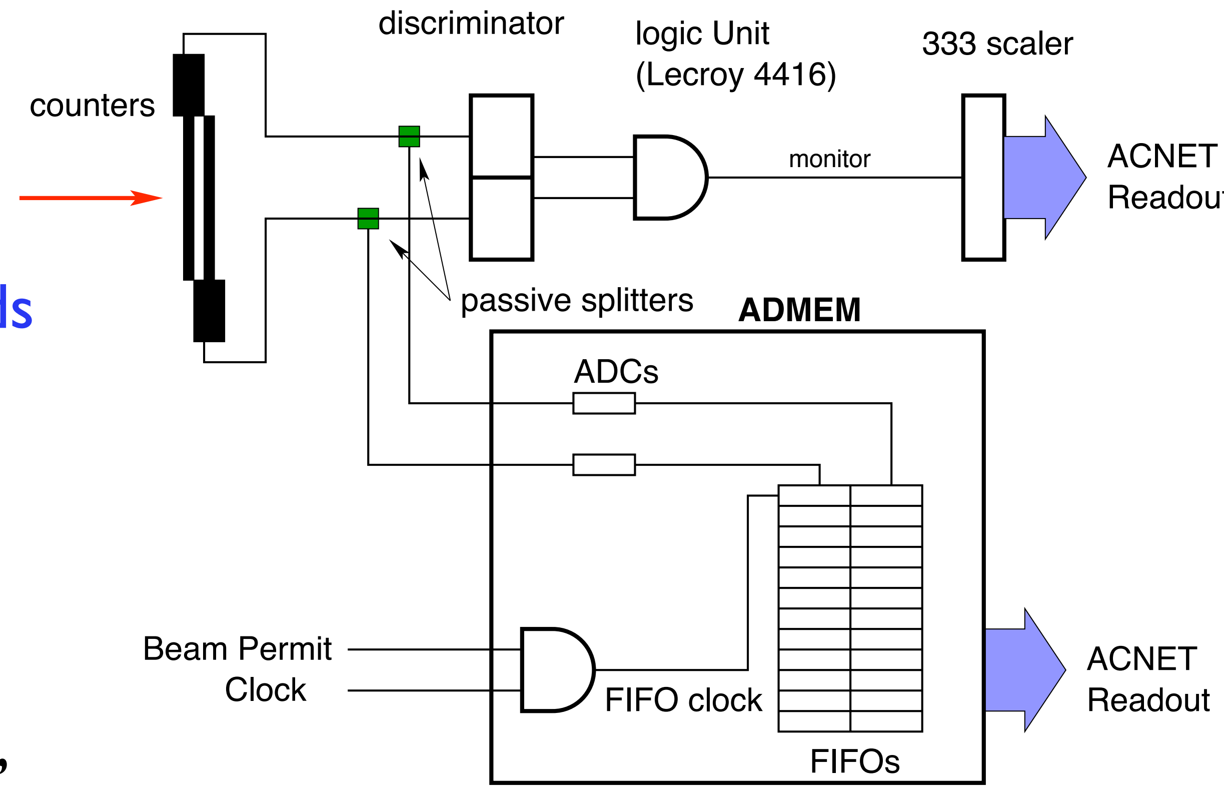
proton abort gap

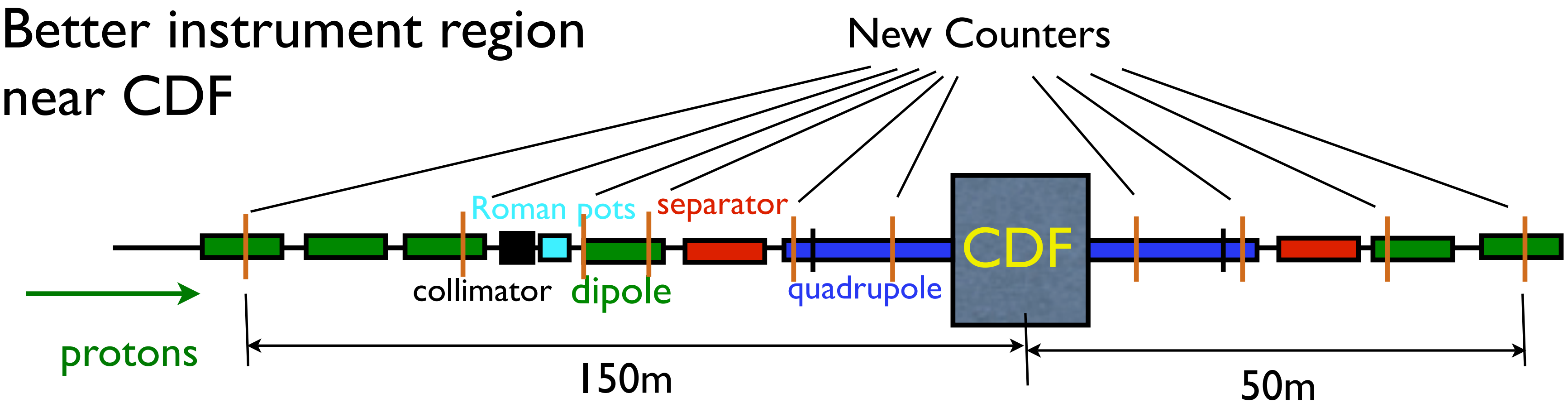
proton halo

proton losses

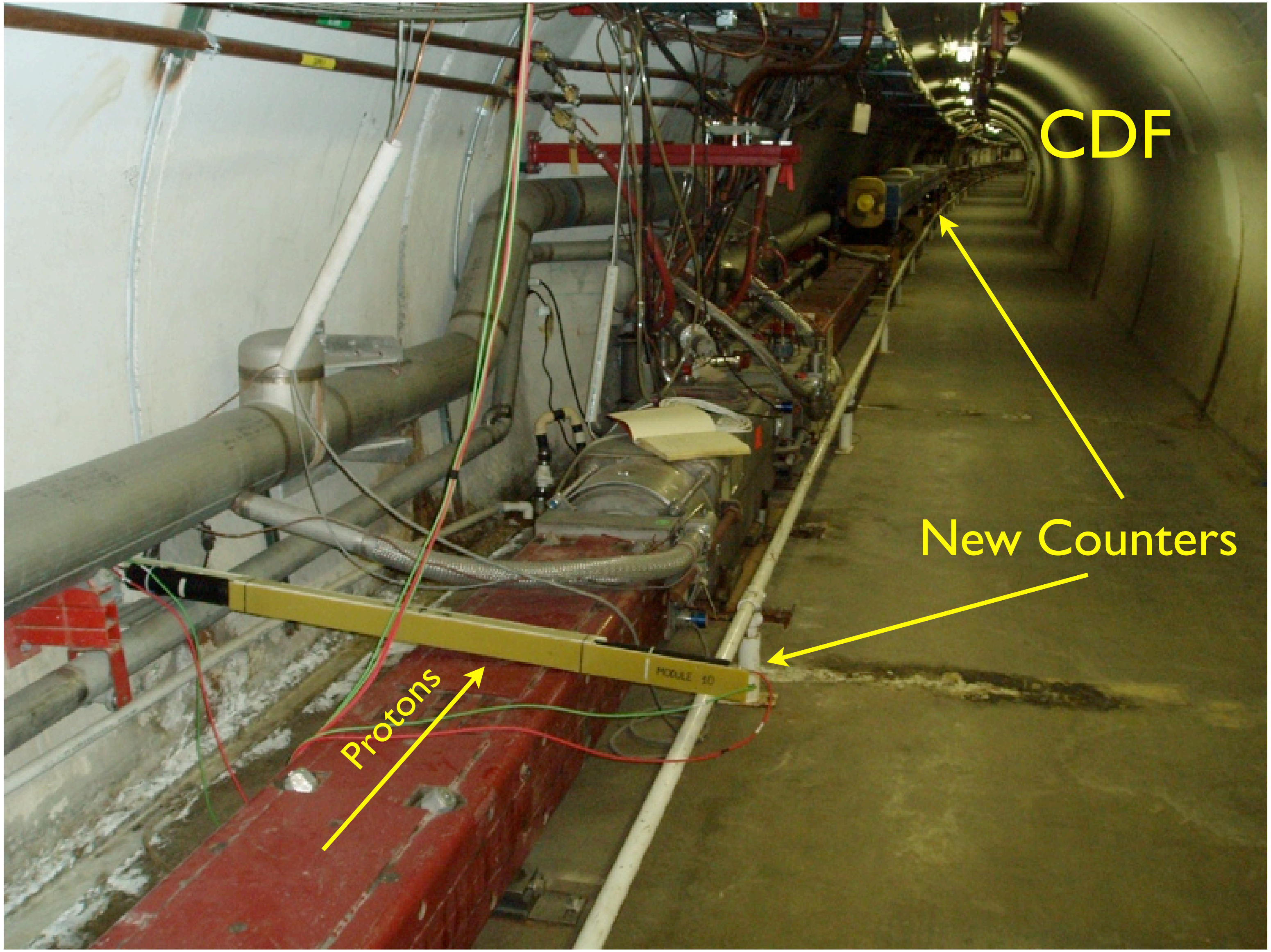
New Halo/Loss System in 2006

- 2 Counter coincidence
  - Suppress backgrounds
  - Calibrate *in situ*
- Additional Electronics
  - Digitize every bunch
  - Deep FIFO (record several revolutions)
- Reconstruct "accidents"
- Better instrument region near CDF





New Halo/Beam Abort System

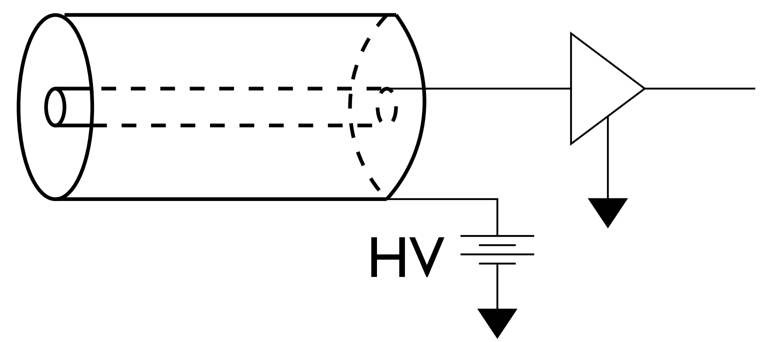


System being commissioned!

Beam Loss Monitors (BLM)

Cylindrical Ionization Chamber

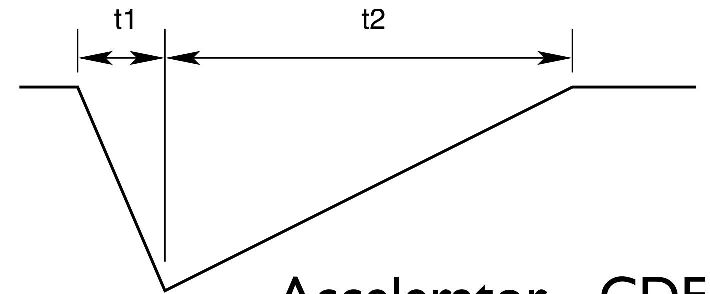
- 110 cc Ar @ atmospheric pressure
- measure ionization ~ beam losses



Part of Tevatron abort system

- continuously sample losses (ungated)
- samples every 10 turns, abort on any turn above programmable threshold.
- Conversion 70nA/(rad/s)

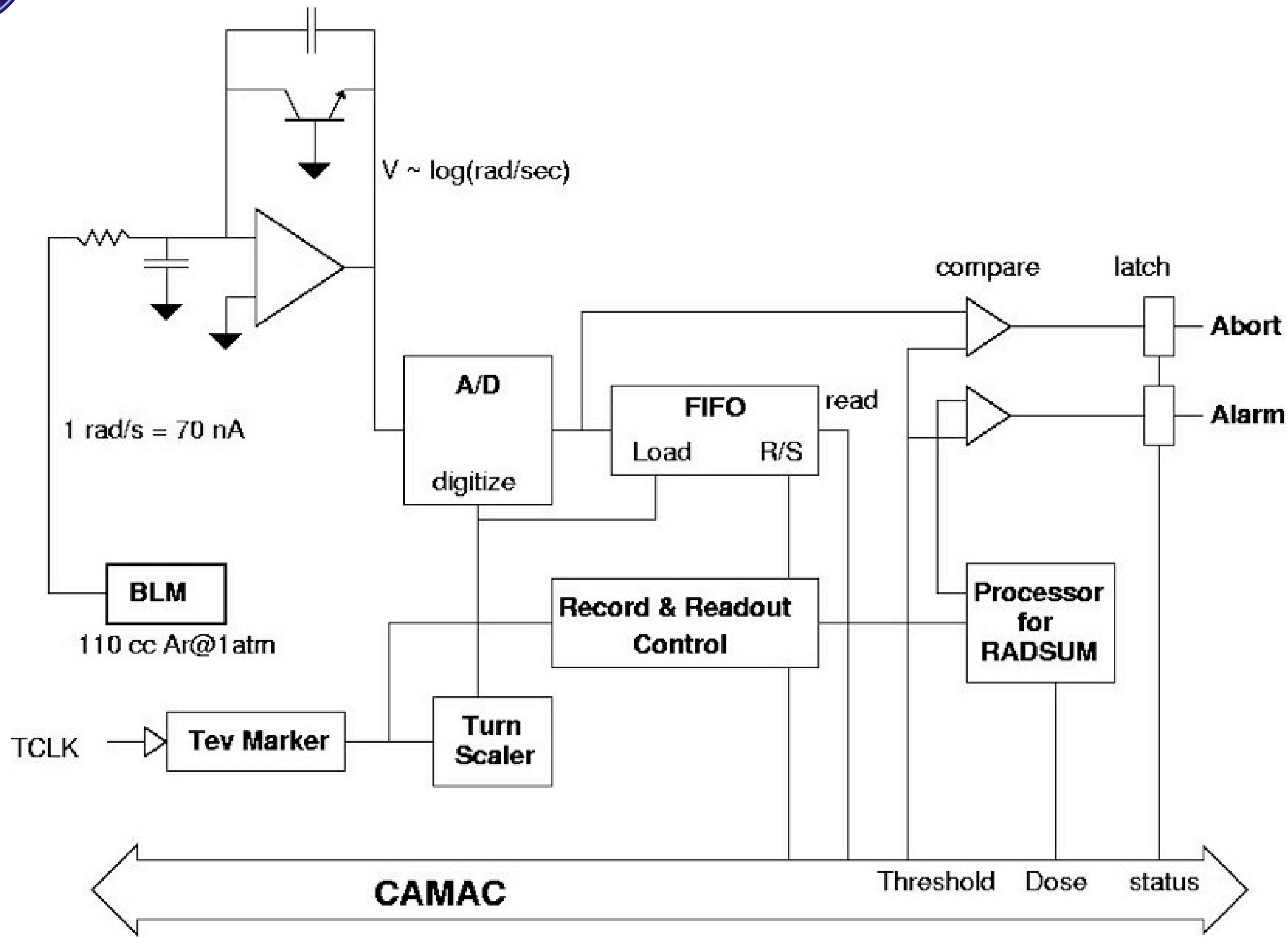
Signal Shaping



	Accelerator	CDF/D0
t1	24µs	24µs
t2	67ms	940ms

Note: Tevatron revolution time = 21 µs

BLM Electronics



Electronics upgrade 2006-7 to VME based system

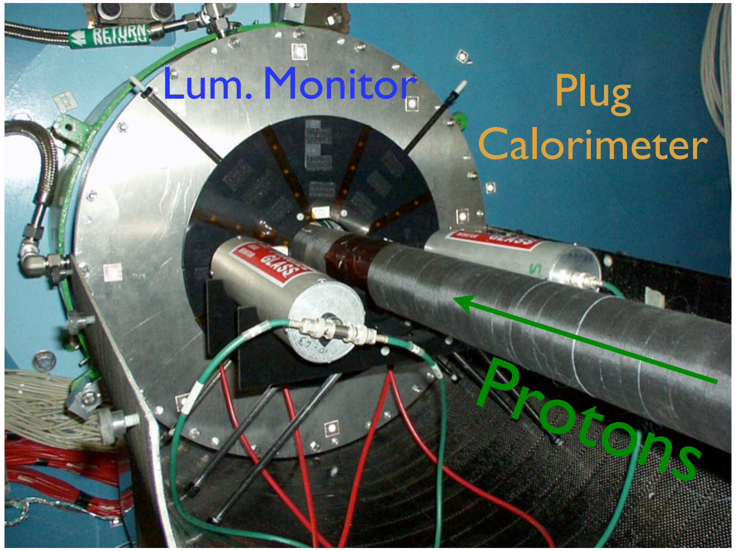
o faster sampling/abort capability

BLMs Locations

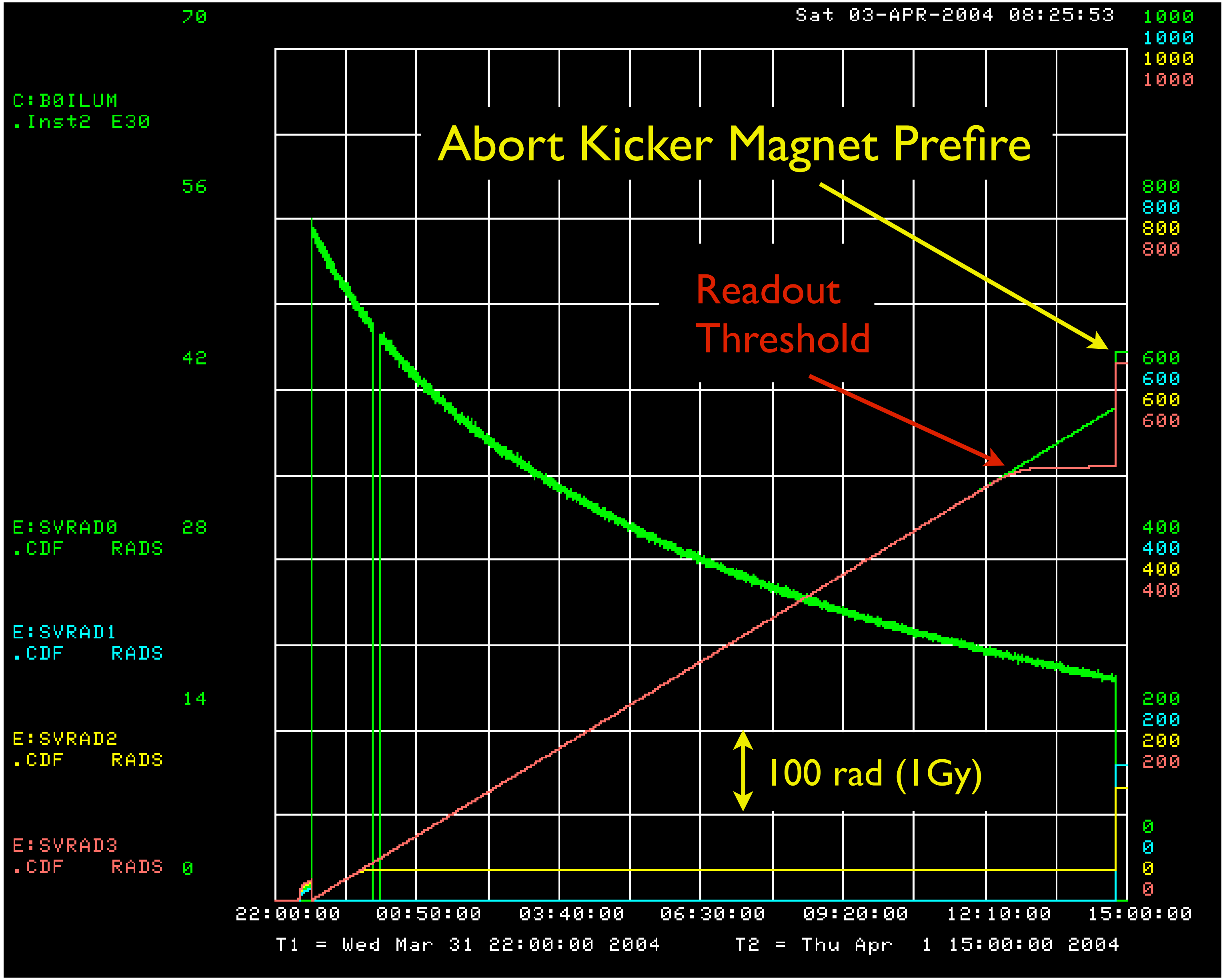
BLM package

Accelerator Tunnel

CDF



BLM Data



Proton-inner

Pbar-outer

Luminosity

Proton-outer

Pbar-inner

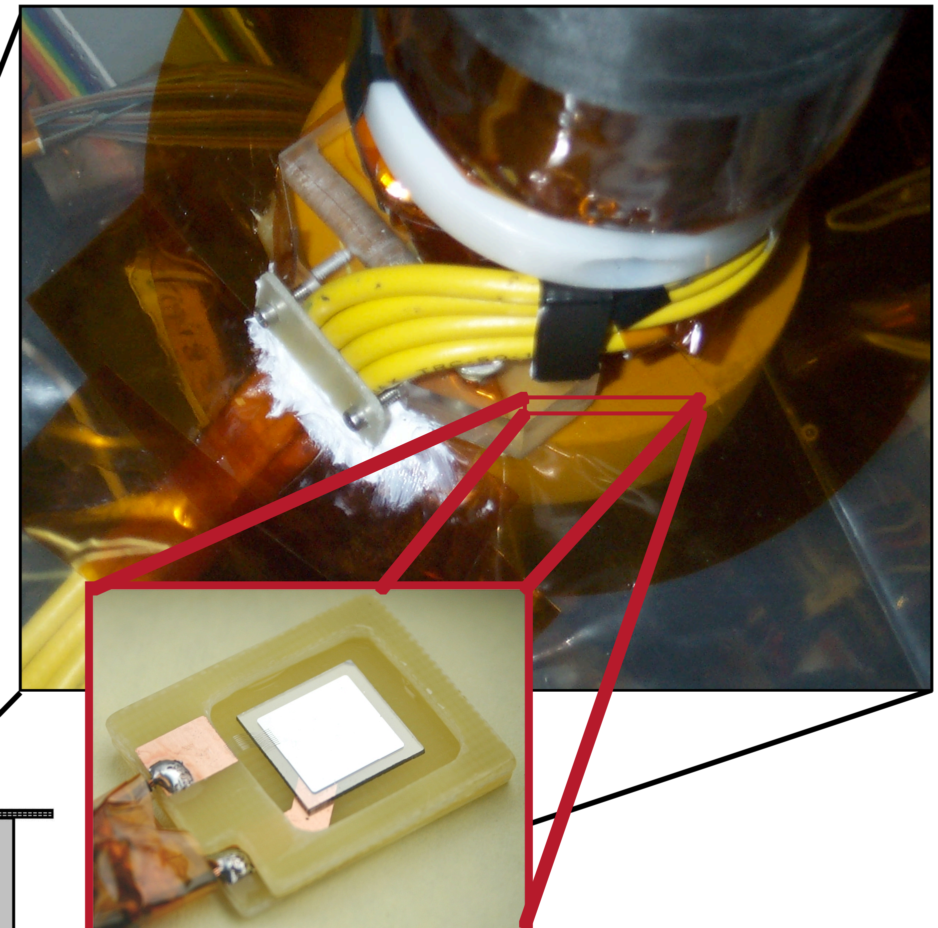
Diamond Beam Monitors

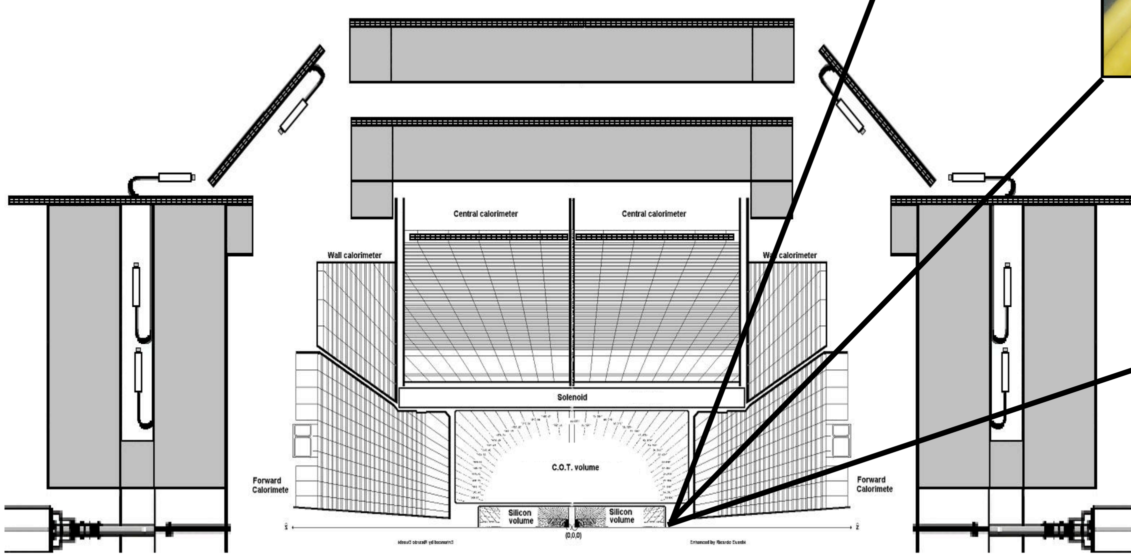
Monitor near SVX

- small
- radiation tolerant
- fast

New BLM electronics

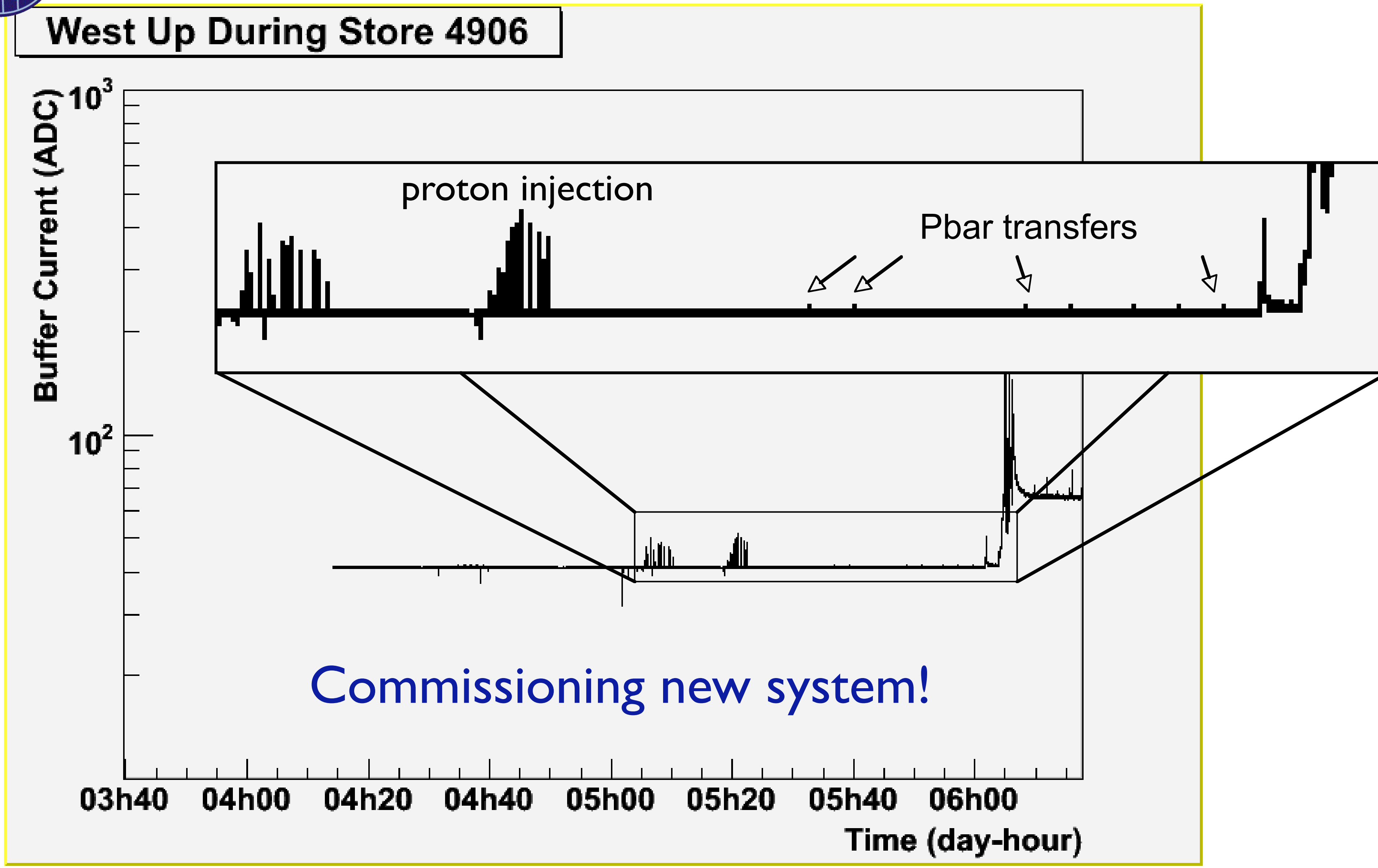
- no development time





R. Eusebi, et al.

Diamond Beam Monitors

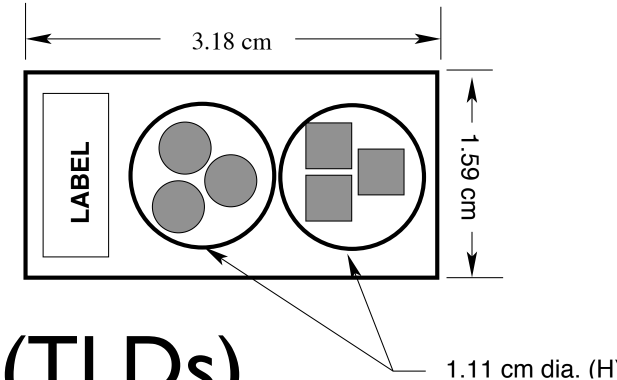


R. Eusebi, et al.

Radiation Field Maps

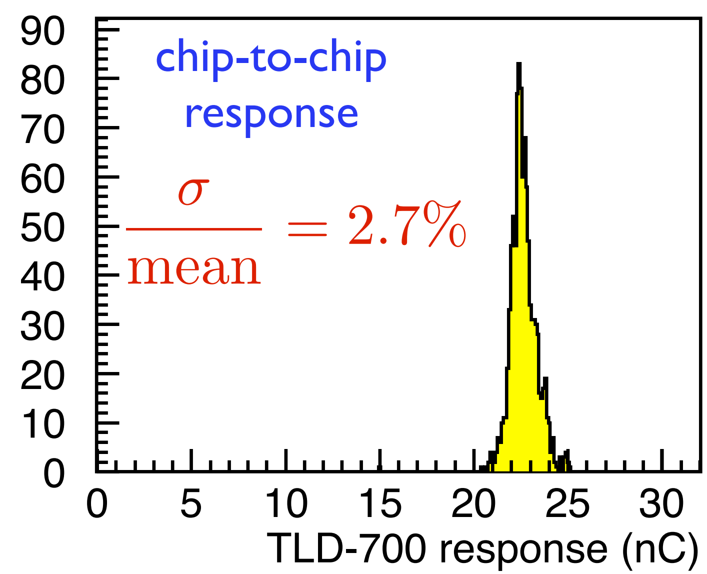
Measure Radiation Field

- understand environment
- calibrate simulations

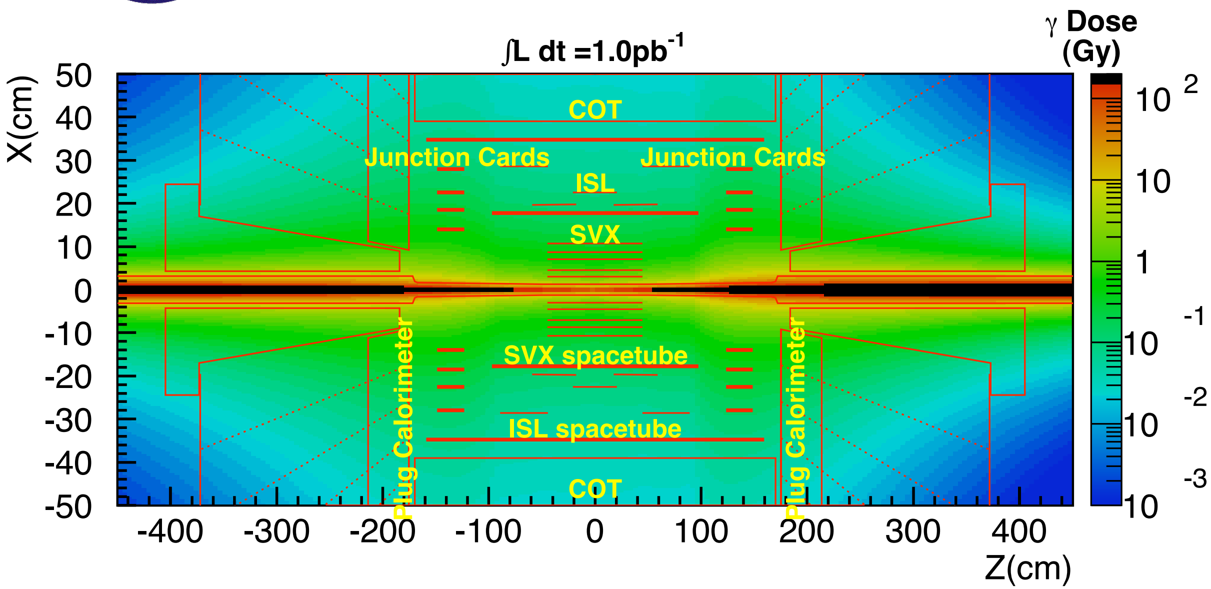


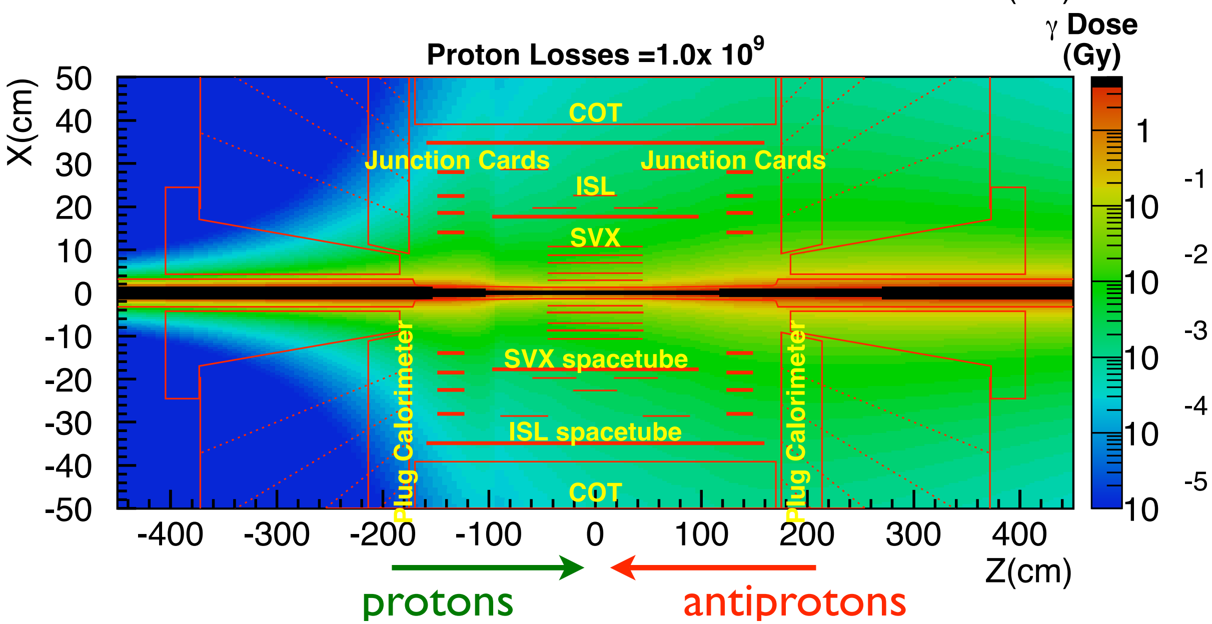
Thermal Luminescent Dosimeters (TLDs)

+ passive
+ accurate measurement of radiation
+ good dynamic range (10^{-3} - 10^{2} Gy)
+ γ,n measurements
+ absolute calibration
- harvest to read
- large amount of handling
- non-linearity at high doses
- only measure “thermal” neutrons



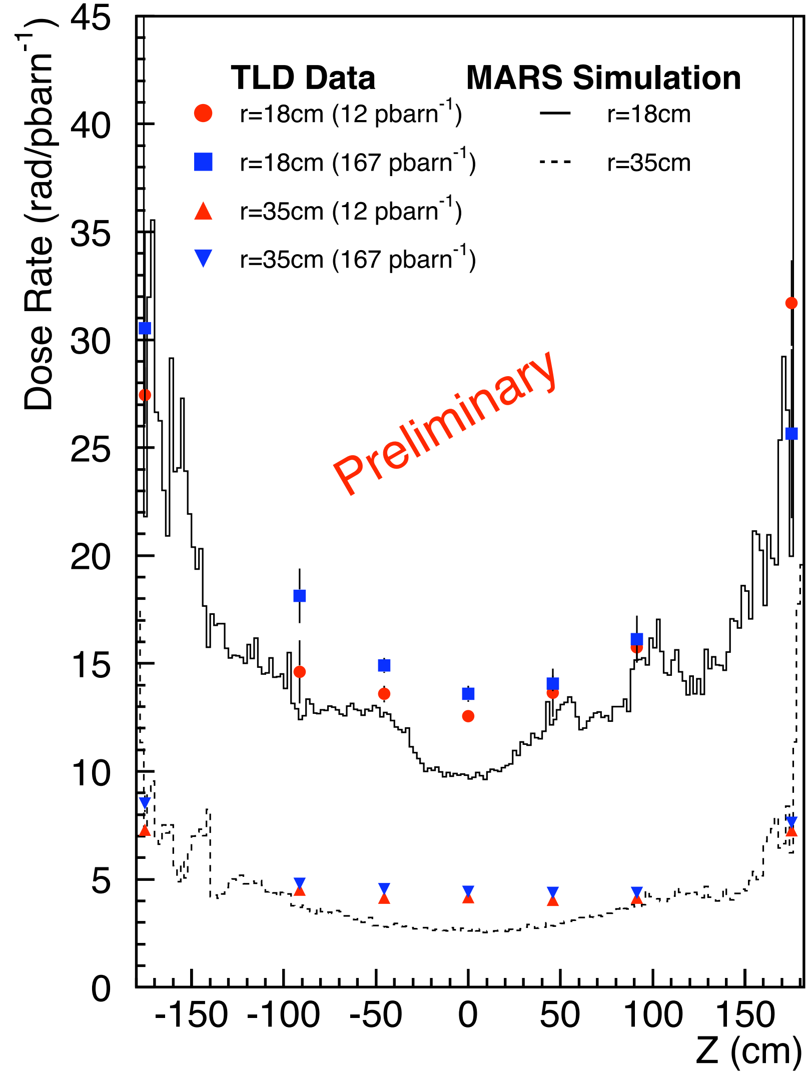
Tracking Volume Ionizing Radiation





Absolute Normalization

3 months tuning simulation



http://ncdf67.fnal.gov/~tesarek/radiation/iondose.html

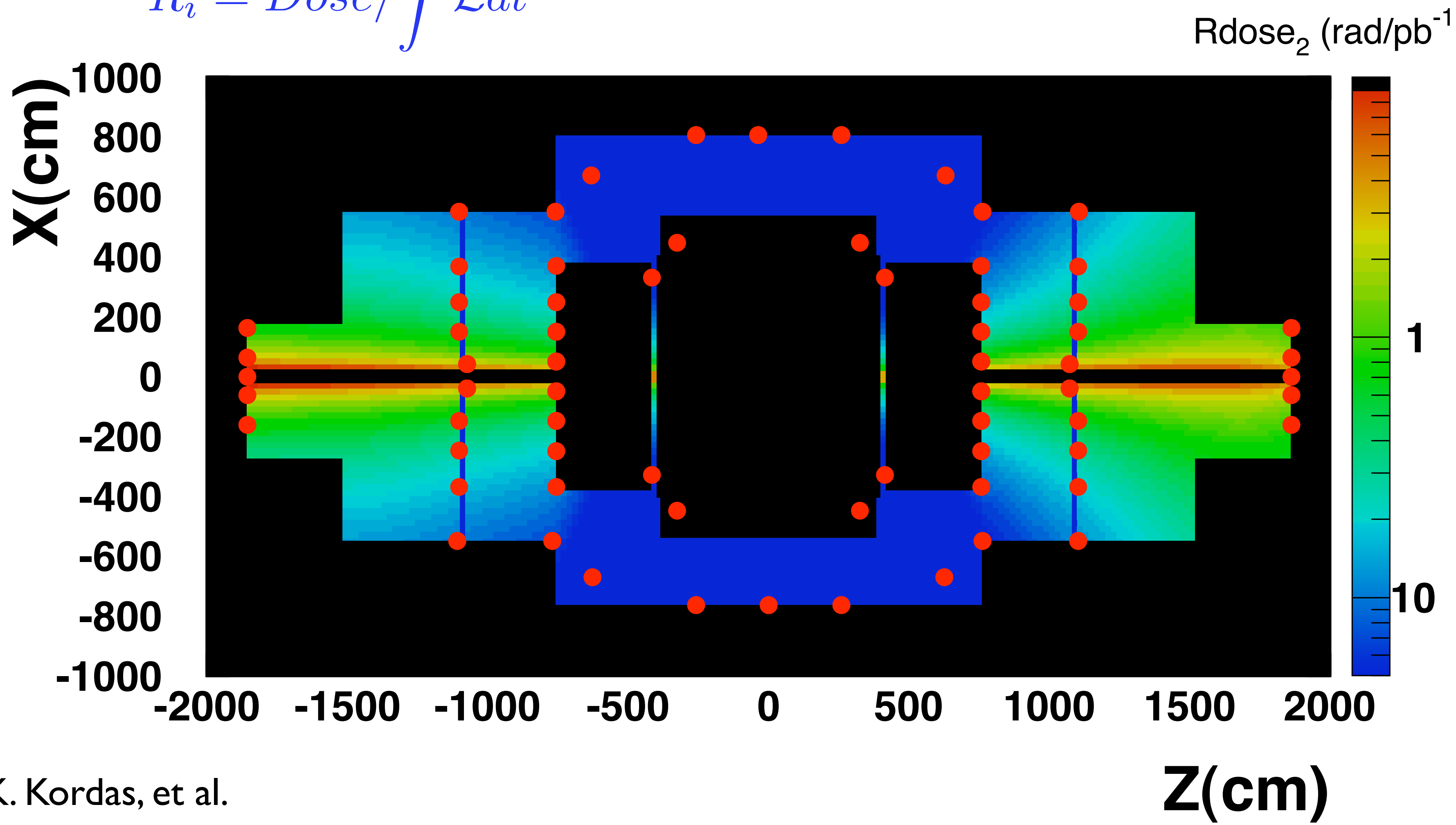
Collision Hall Ionizing Radiation

960 dosimeters installed in 160 locations
Radiation field modeled by a power law

$$Dose = \frac{A}{r^{\alpha}}$$

r is distance from beam axis

$$R_i = Dose / \int \mathcal{L} dt$$



K. Kordas, et al.

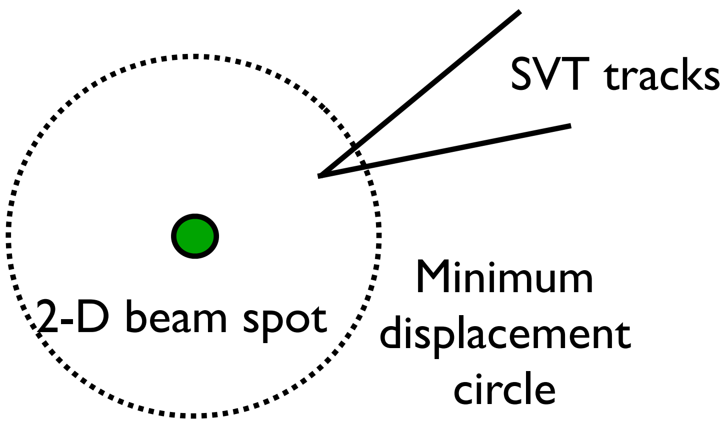
Silicon Vertex Trigger (SVT)

Trigger on tracks displaced from beam

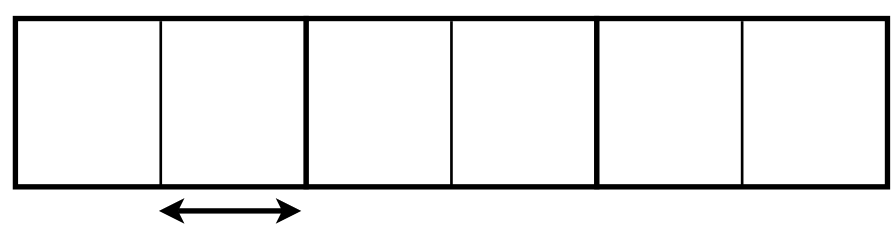
- real time average beam position measurement ($\sigma \sim 50\ \mu m$)
- multiple position measurements gives beam slope

Knowledge of beam position crucial for trigger

Helpful in minimizing localized radiation damage



SVX Detector



6 beam position measurements

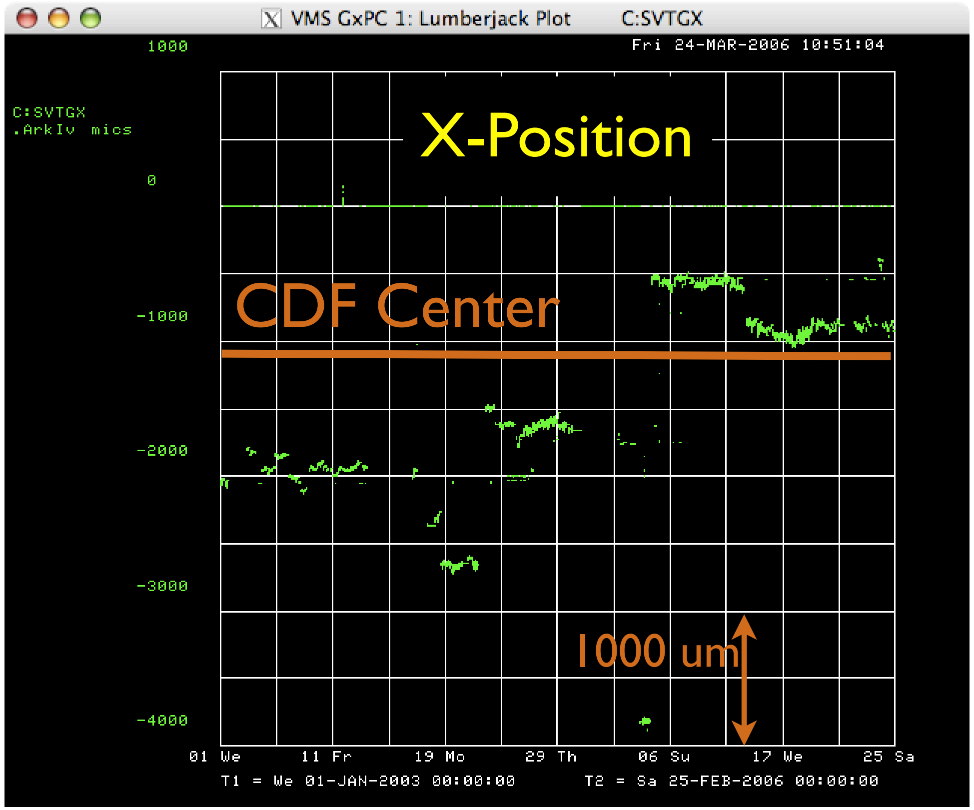
4mm beam offset yields a dose profile which varies by factor of 3 as a function of phi for L00 (r = 1.3cm).

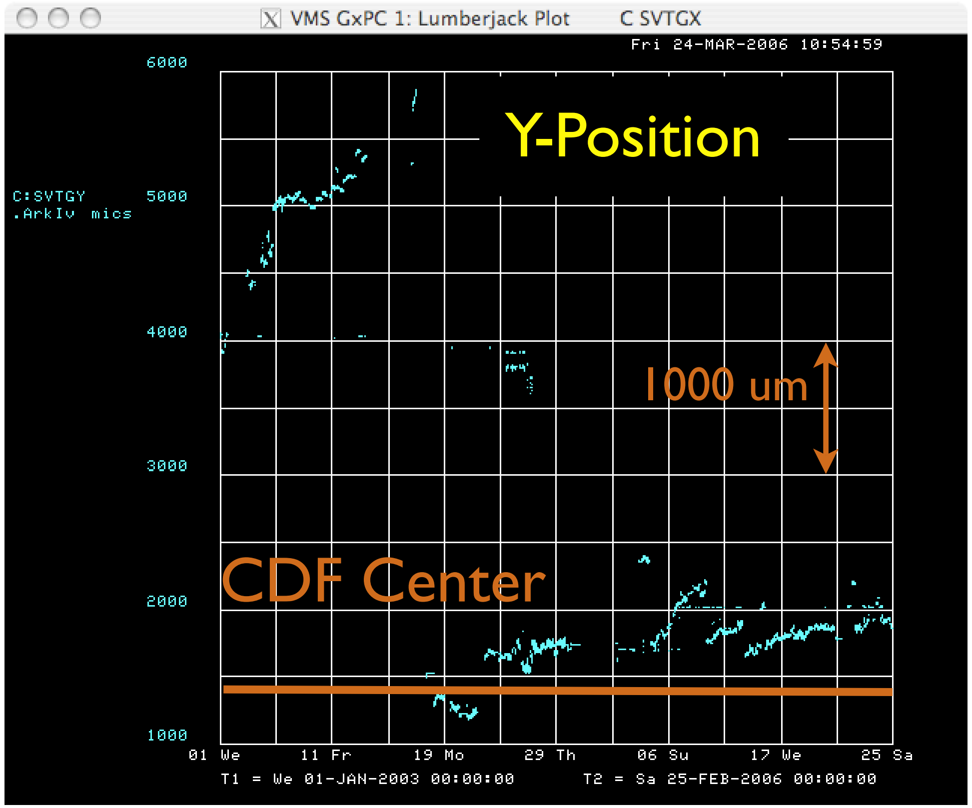
Beam Position in CDF

Beam position and slope measured in real time using SVT

POSITION	ACNET	CDF Center
Horizontal (x)	C:SVTGX	-1160 um
Vertical (y)	C:SVTGY	1436 um

History: 1/1/03 - 2/25/06



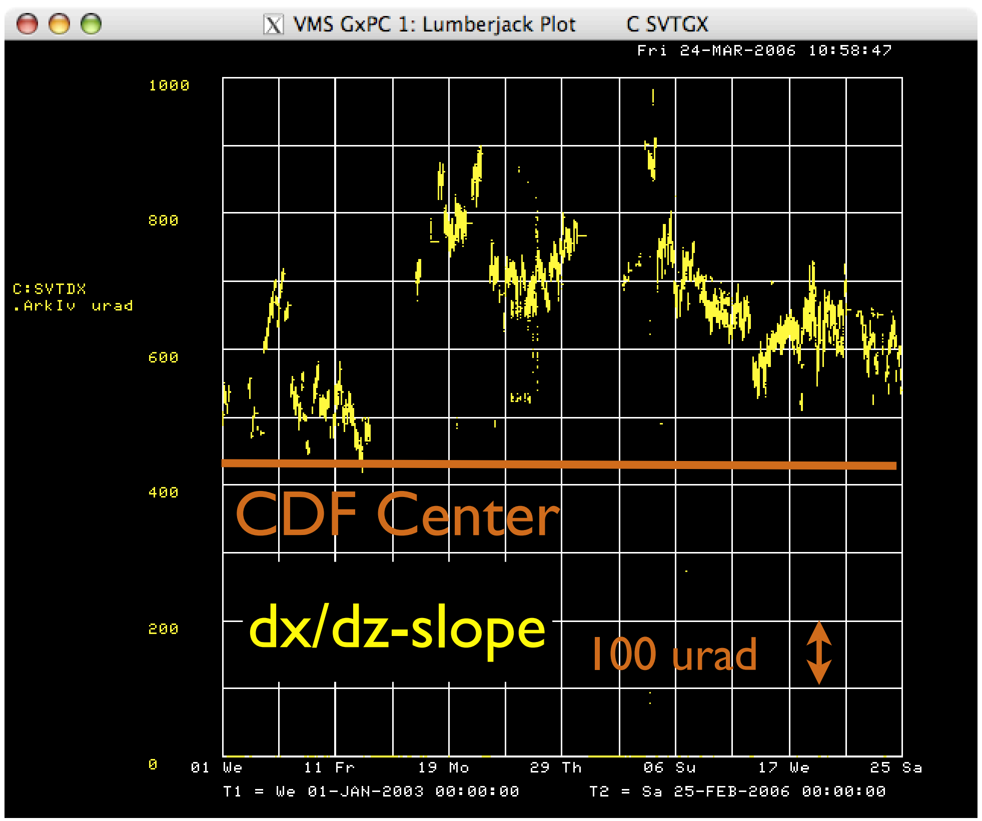


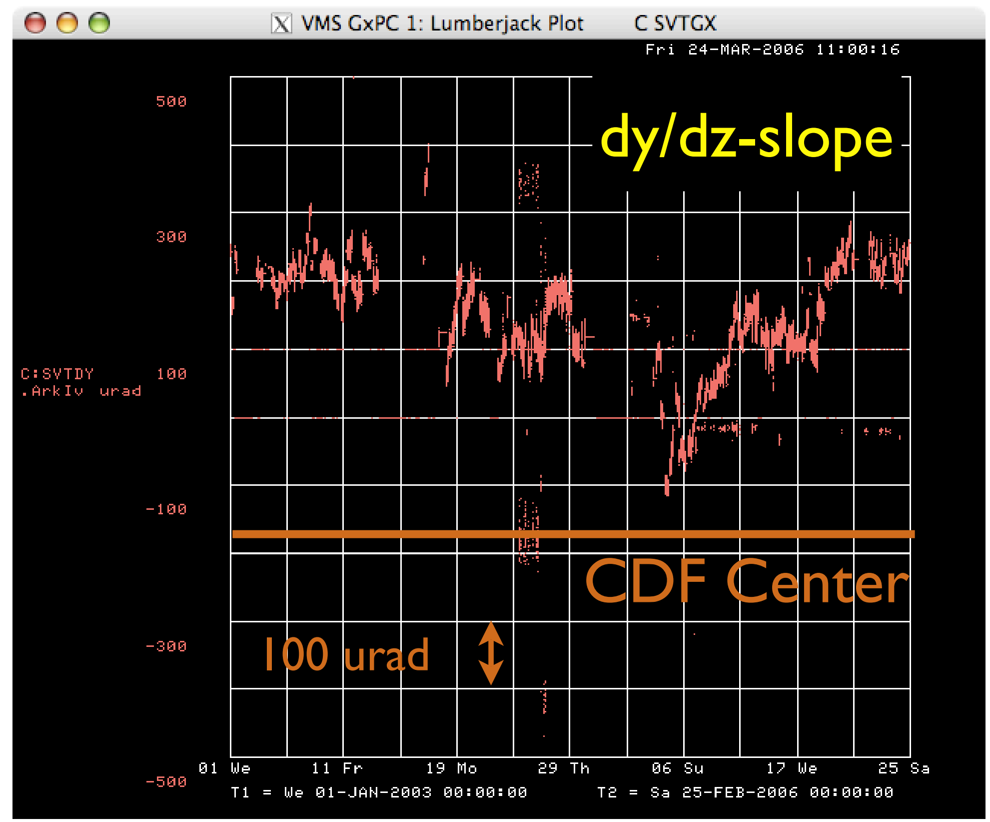
Beam Trajectory Thru CDF

Beam position and slope measured in real time using SVT

SLOPE	ACNET	CDF Center
Horizontal (dx/dz)	C:SVTDX	417 urad
Vertical (dy/dz)	C:SVTDY	-190 urad

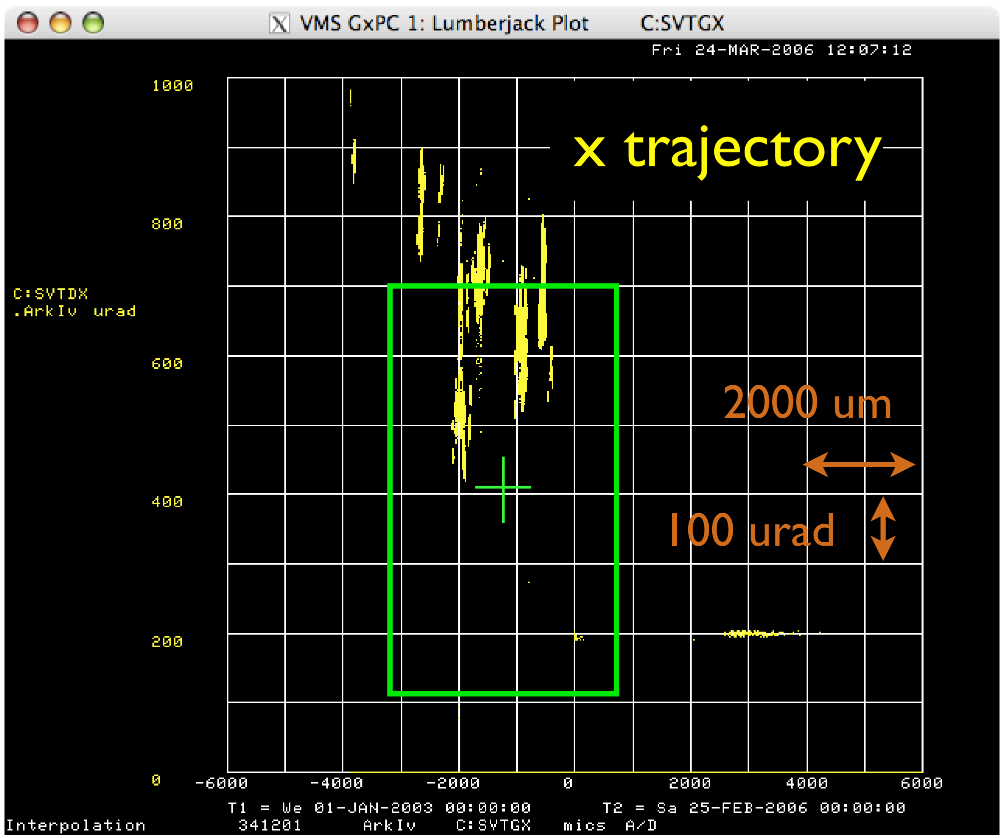
History: 1/1/03 - 2/25/06

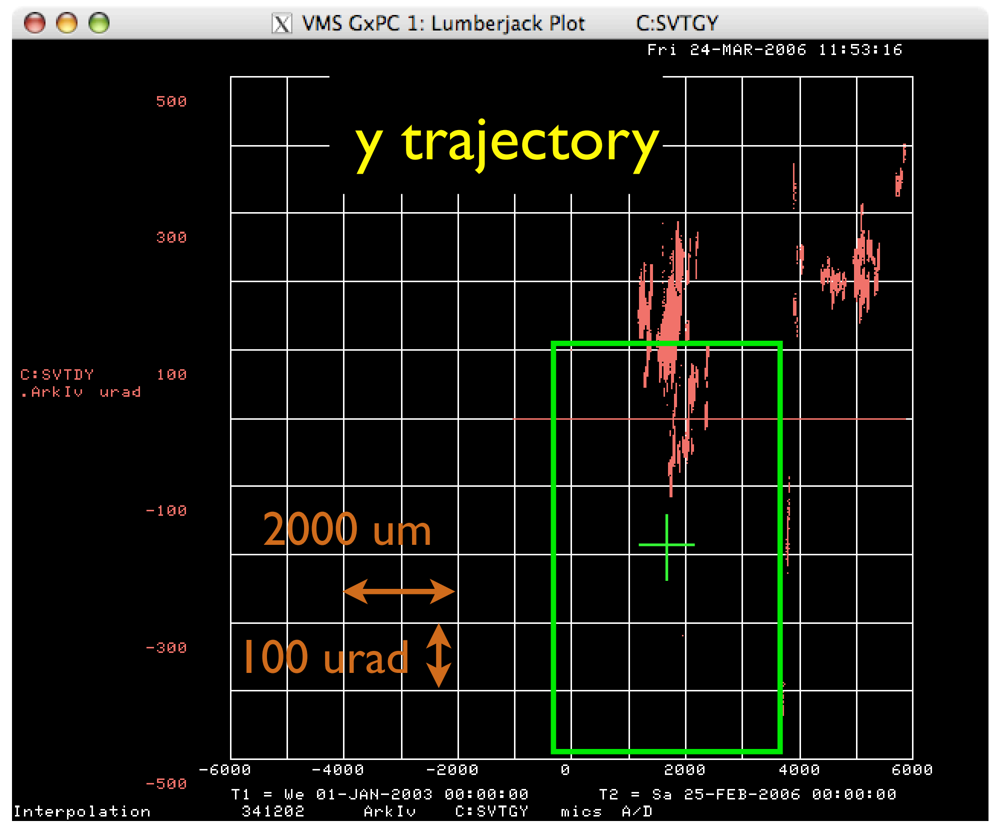




Beam Trajectory Tolerances

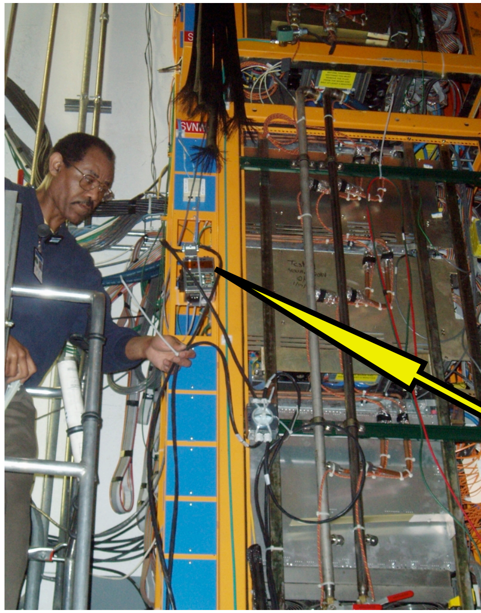
Define X and Y trajectory tolerances (boxes)





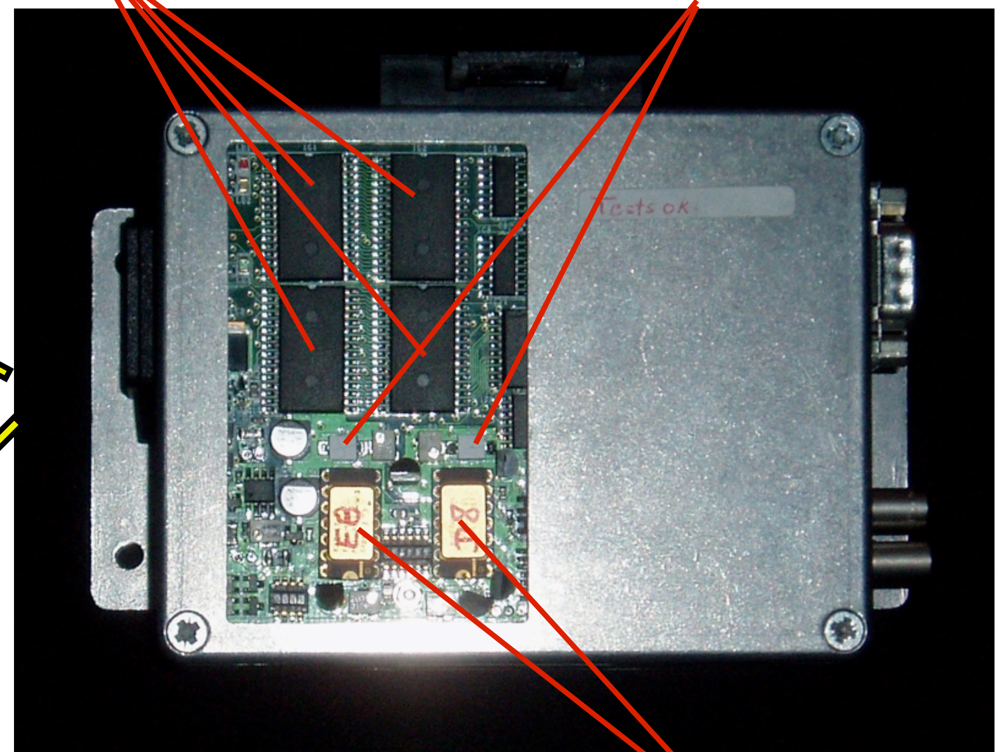
Accelerator operators adjust beam to hit inside boxes

Active Dosimeters



SEU counters (memories)
>20 MeV hadrons

PIN diodes
1 MeV n equivalent

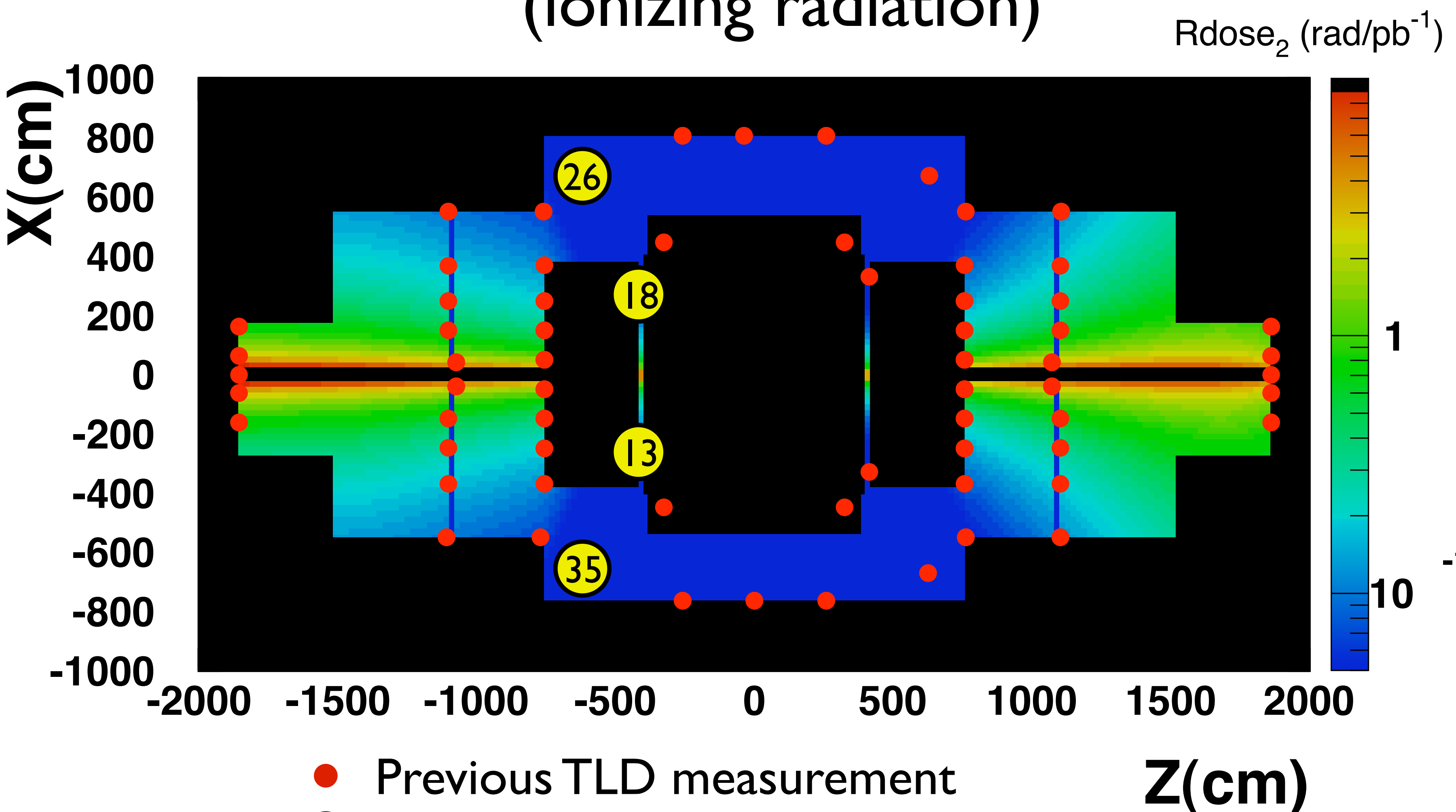


RadFETs
γ–e dose

Thijs Wijnands, Christian Pignard

Located near sensitive electronics
Readout at ~0.1 Hz
LHC prototype

CDF Radiation Field
(ionizing radiation)



● Previous TLD measurement

○ CERN Dosimeter Location/ no. SEU

Exposure Period: 27 April - 28 September 2005

TEVMON

STATUS OF BEAM CONDITIONS

(Generated by TevMon every 10 seconds)

Latest Update: 12-Jan-03 12:33:37

SILICON DANGER IDLE

NO SCRAPING YET (OR NO BEAM IN MACHINE)

NAME OF VARIABLE	STATUS	T(1 min)	T(5 min)	T(10 min)
MEAN (LOSTP)	OK	198.4375 Hz	198.4375 Hz	198.4375 Hz
RMS (LOSTP)	OK	0.0 (%)	1.3593188E-6 (%)	4.2985434E-6 (%)
MEAN (LOSTPB)	OK	-176.5625 Hz	-176.5625 Hz	-175.72917 Hz
RMS (LOSTPB)	IDLE	0.0 (%)	5.04637E-4 (%)	448.76373 (%)
MEAN (L1COLI)	IDLE	0.17903645 mA	0.18229167 mA	0.18208821 mA
RMS (L1COLI)	IDLE	3.2141218 (%)	3.8403237 (%)	4.291143 (%)
MEAN (B0PAGC)	OK	0.0 Hz	0.0 Hz	0.20047987 Hz
RMS (B0PAGC)	OK	0.0 (%)	0.0 (%)	300.00446 (%)
MEAN (RFSUM)	OK	1.0776666 MV/T	1.0776666 MV/T	1.0777042 MV/T
RMS (RFSUM)	OK	0.028933324 (%)	0.034059256 (%)	0.028565757 (%)
MEAN (RFSUMA)	OK	1.1326667 MV/T	1.1327916 MV/T	1.1328083 MV/T
RMS (RFSUMA)	OK	0.02752838 (%)	0.027964216 (%)	0.027138846 (%)
MEAN (B0ILUM)	IDLE	0.0 cm-2s-1	0.0 cm-2s-1	0.0 cm-2s-1
RMS (B0ILUM)	IDLE	0.0 (%)	0.0 (%)	0.0 (%)

TevMon Home Page

Important DAQ Processes Page

Automate monitoring

- rapid response
- web based
- used in main control room

CDF Experience

Rate of permanent damage to SVX reduced

- better understanding of detector
- automate monitoring conditions of high risk
  - unstable beam (wide RMS for losses)
  - high losses
  - RF voltages
  - bunch length (precursor of debunched beam)
  - beam in abort gaps

Improved TeV performance

- higher luminosity
- lower losses
- reduced halo

Good communication with Main Control Room

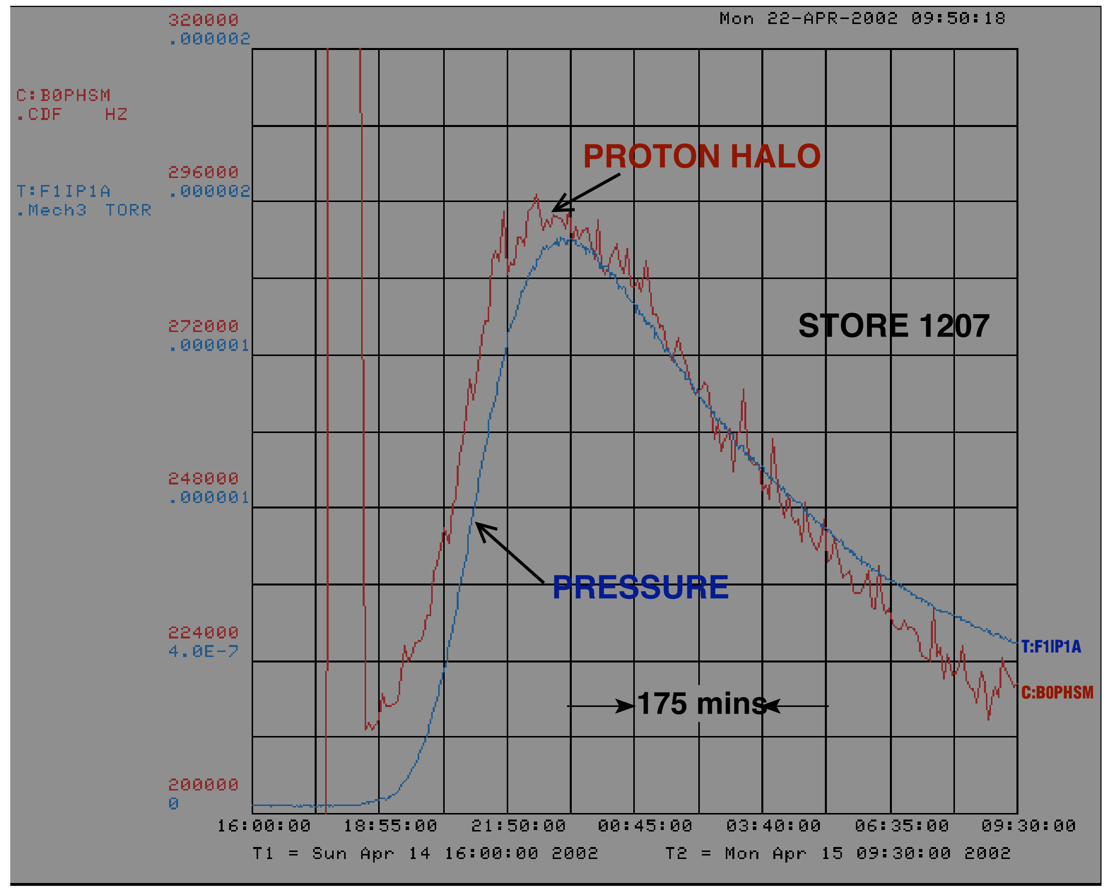
Halo Reduction

Vacuum problems identified in 2m long straight section of Tevatron (F sector)

Improved vacuum (TeV wide)

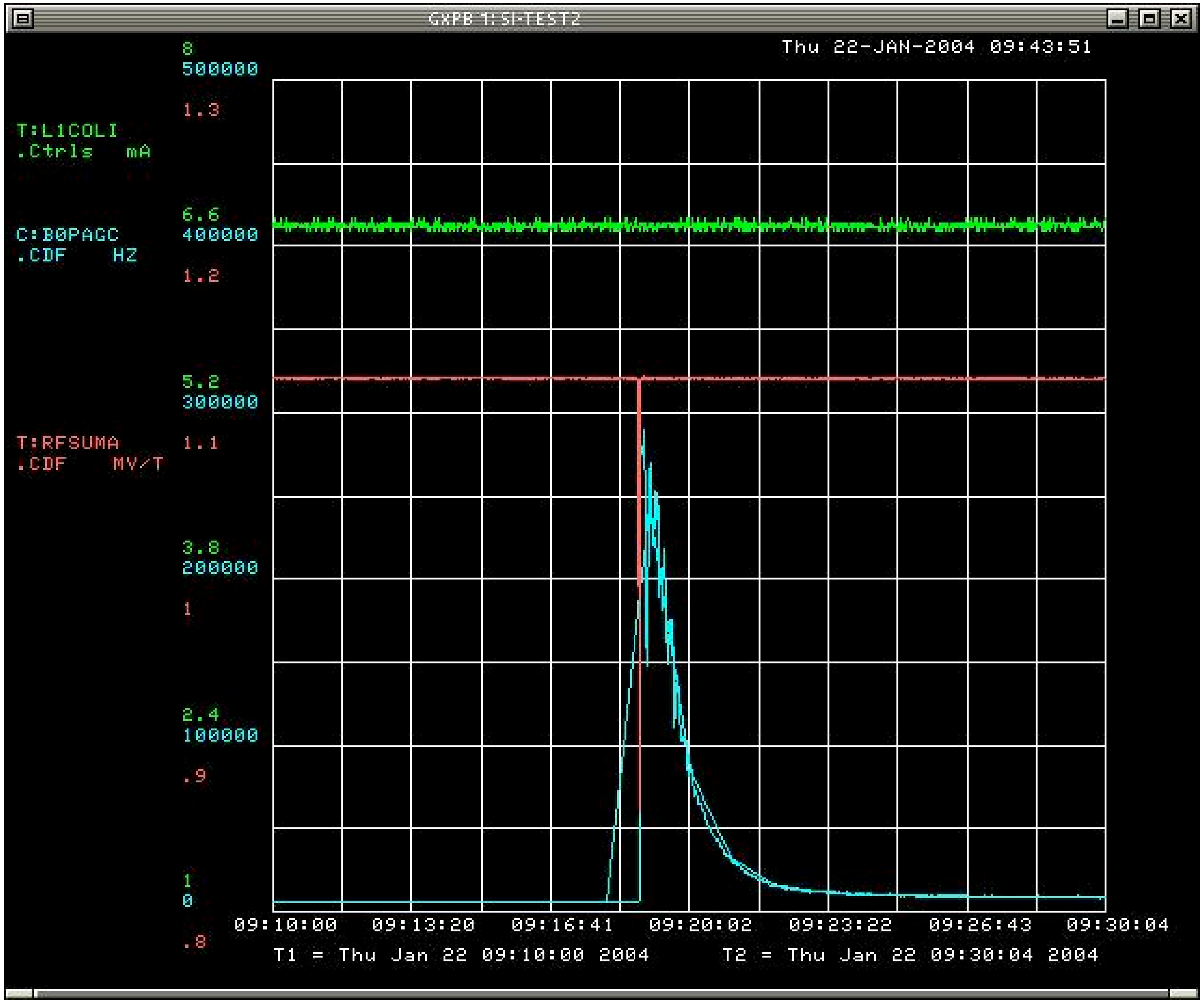
Commissioning of collimators to reduce halo

> Physics backgrounds reduced by ~40%



R. Moore, V. Shiltsev, N.Mokhov, A. Drozhdin

RF Problem (spark?)



T:L1COLI

T:RFSUMA

Beam driven from bunches by RF spark.

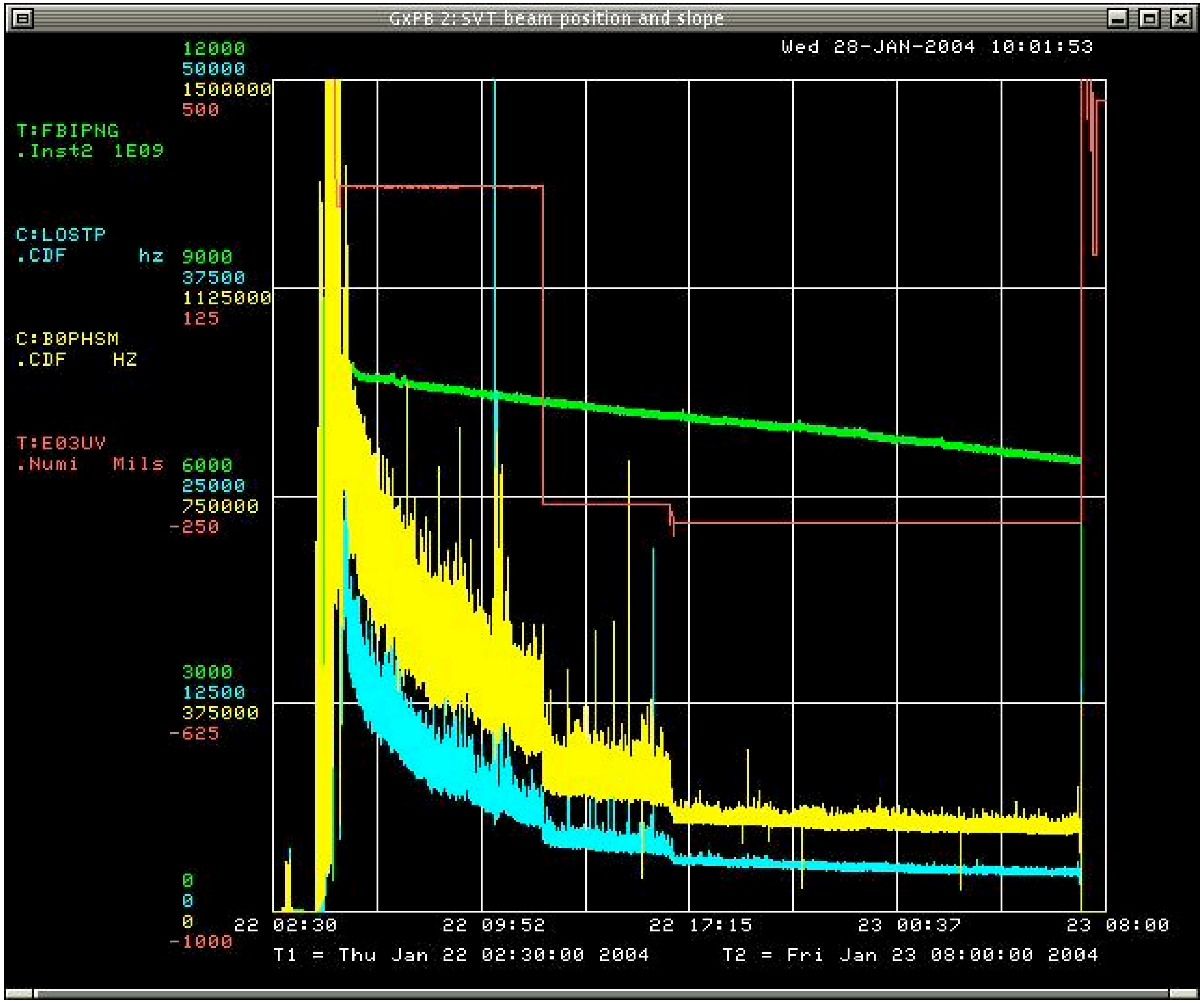
Increase in abort gap proton losses.

Electron Lens removes beam from abort gap.

C:B0PAGC

Beam Collimation

Background reduction at work



E0 collimator

proton beam current

proton halo

proton losses

Typical Store(2004)

Beam Parameters:

Protons:	5000 - 9000	10^9 particles
Antiprotons:	100-1500	10^9 particles
Luminosity:	10 - 50	$10^{30}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Losses and Halo:

Quantity	Rate (kHz)	Limit (kHz)	comment
P Losses	2 - 15	25	chambers trip on over current
Pbar Losses	0.1 - 2.0	25	chambers trip on over current
P Halo	200 - 1000	-	
Pbar Halo	2 - 50	-	
Abort Gap Losses	2 - 12	15	avoid dirty abort (silicon damage)
L1 Trigger	0.1-0.5		two track trigger (~1 mbarn)

Note: All number are taken after scraping and HEP is declared.

Typical Store (2005)

Color Codes

better than 2004
worse than 2004
no change

Beam Parameters:

Protons:	5000 - 10000	10^9 particles
Antiprotons:	500-1800	10^9 particles
Luminosity:	50 - 170	$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Losses and Halo:

Quantity	Rate (kHz)	Limit (kHz)	comment
P Losses	0.1 - 0.5	25	chambers trip on over current
Pbar Losses	0.1 - 3.0	25	chambers trip on over current
P Halo	15 - 18	-	
Pbar Halo	20 - 100	-	
Abort Gap Losses	0.1 - 15	25	avoid dirty abort (silicon damage)
L1 Trigger	0.1-0.5		two track trigger (~1 mbarn)

Note: All number are taken after scraping and HEP is declared.

Crucial Instruments Omitted

Tevatron Electron Lens (TEL)

- TEL induces betatron oscillations in beam when on
- used for cleaning abort gaps & beam-beam compensation
- http://www-bd.fnal.gov/lug/tev33/ebeam_comp/

Synchrotron Light Measurements

- used to monitor DC beam (beam in abort gaps)
- http://home.fnal.gov/~cheung/synclite/

Beam Position Monitors

- measure beam position around accelerator

Collimators

- remove halo surrounding beam at safe locations (away from CDF)

What did we do right?

Fast, aggressive reaction to problems

Keep it simple (KIS)

- used existing instrumentation
- added simple scintillation counters & logic
- redundant measurements
- studies with dosimeters
- automated monitoring

Develop understanding of accelerator

- instrumentation
- consult accelerator physicists to reduce risk from beam

Documented our work

- web pages
- internal notes

What did we do wrong?

Reacted to problems we could have anticipated

- lack of shielding
- little initial understanding of accelerator

Few, poorly understood beam monitors

- initially little/no documentation

No local accelerator expertise

Initial instrumentation lifetime

- radiation damage to scintillator
- no in-situ calibration

Summary

Multiple, redundant systems provide good monitors of beam conditions.

Detector technologies used at CDF

- Cherenkov counters
- scintillation counters
- ionization chambers
- Diamond detectors
- CERN "RadMon" Monitors

Only useful in combination w/accelerator information.

Close work with accelerator physicists required.

References (Incomplete List)

General:

- http://ncdf67.fnal.gov/~tesarek
- http://www-cdfonline.fnal.gov/acnet/ACNET_beamquality.html

CDF Instrumentation:

- M.K. Karagoz-Unel, R.J. Tesarek, *Nucl. Instr. and Meth.*, **A506** (2003) 7-19.
- A.Bhatti, *et al., CDF internal note*, **CDF 5247**.
- D. Acosta, *et al., Nucl. Instr. and Meth.*, **A494** (2002) 57-62.
- R.J. Tesarek, *CDF internal note,* **CDF 7853** (2005).

Beam Monitoring Variables:

- http:/www-cdfonline.fnal.gov/ops/acnet/ACNET_beamquality

Beam Halo and Collimation:

- A. Drozhdin, *et al., Proceedings: Particle Accelerator Conference(PAC03),* Portland, OR, 12-16 May 2003.
- L.Y. Nicolas, N.V. Mokhov, *Fermilab Technical Memo:* **FERMILAB-TM-2214** June (2003).

Beam Backgrounds:

- R.J. Tesarek, *CDF internal note,* **CDF 5873** (2002).
- M.Lindgren, *et al., CDF internal note,* **CDF 5960** (2002).
- M.Albrow, *et al., CDF internal note,* **CDF 5926** (2002).

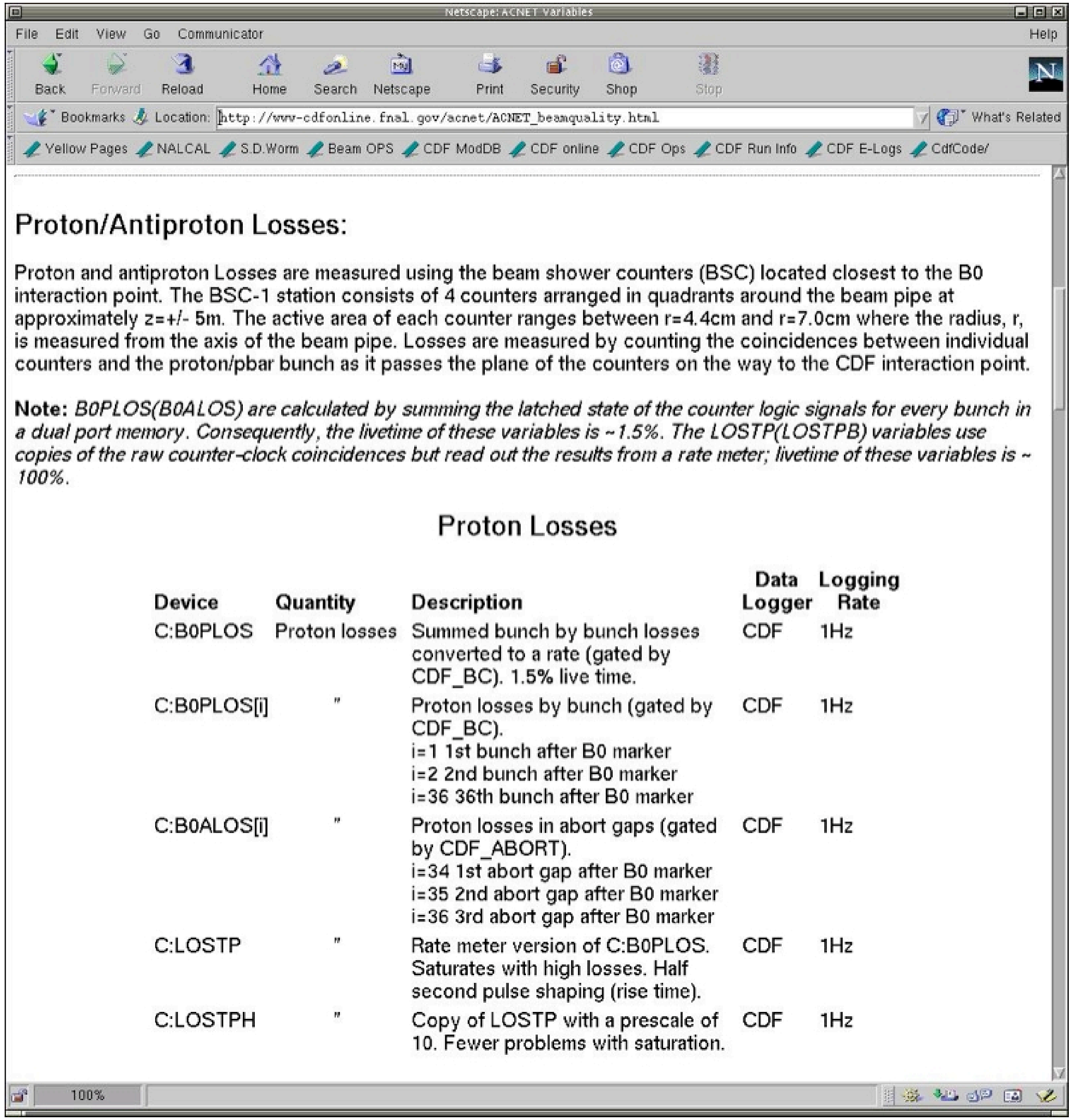
References (cont...)

Radiation:

- D. Amidei, *et al., Nucl. Instr. and Meth.,* **A320** (1994) 73.
- S. d'Auria, *et al., Nucl. Instr. and Meth.,* **A513** (2003) 89-93.
- K. Kordas, *et al., Proceedings: IEEE-NSS/MIC Conference,* Portland, OR, November 19-25 (2003).
- R.J. Tesarek, *et al., Proceedings: IEEE-NSS/MIC Conference,* Portland, OR, November 19-25 (2003).

Backup Slides

Documentation



Proton/Antiproton Losses:

Proton and antiproton Losses are measured using the beam shower counters (BSC) located closest to the B0 interaction point. The BSC-1 station consists of 4 counters arranged in quadrants around the beam pipe at approximately z=+/- 5m. The active area of each counter ranges between r=4.4cm and r=7.0cm where the radius, r, is measured from the axis of the beam pipe. Losses are measured by counting the coincidences between individual counters and the proton/pbar bunch as it passes the plane of the counters on the way to the CDF interaction point.

Note: *B0PLOS(B0ALOS) are calculated by summing the latched state of the counter logic signals for every bunch in a dual port memory. Consequently, the livetime of these variables is ~1.5%. The LOSTP(LOSTPB) variables use copies of the raw counter-clock coincidences but read out the results from a rate meter; livetime of these variables is ~ 100%.*

Proton Losses

Device	Quantity	Description	Data Logger	Logging Rate
C:B0PLOS	Proton losses	Summed bunch by bunch losses converted to a rate (gated by CDF_BC). 1.5% live time.	CDF	1Hz
C:B0PLOS[i]	"	Proton losses by bunch (gated by CDF_BC). i=1 1st bunch after B0 marker i=2 2nd bunch after B0 marker i=36 36th bunch after B0 marker	CDF	1Hz
C:B0ALOS[i]	"	Proton losses in abort gaps (gated by CDF_ABORT). i=34 1st abort gap after B0 marker i=35 2nd abort gap after B0 marker i=36 3rd abort gap after B0 marker	CDF	1Hz
C:LOSTP	"	Rate meter version of C:B0PLOS. Saturates with high losses. Half second pulse shaping (rise time).	CDF	1Hz
C:LOSTPH	"	Copy of LOSTP with a prescale of 10. Fewer problems with saturation.	CDF	1Hz

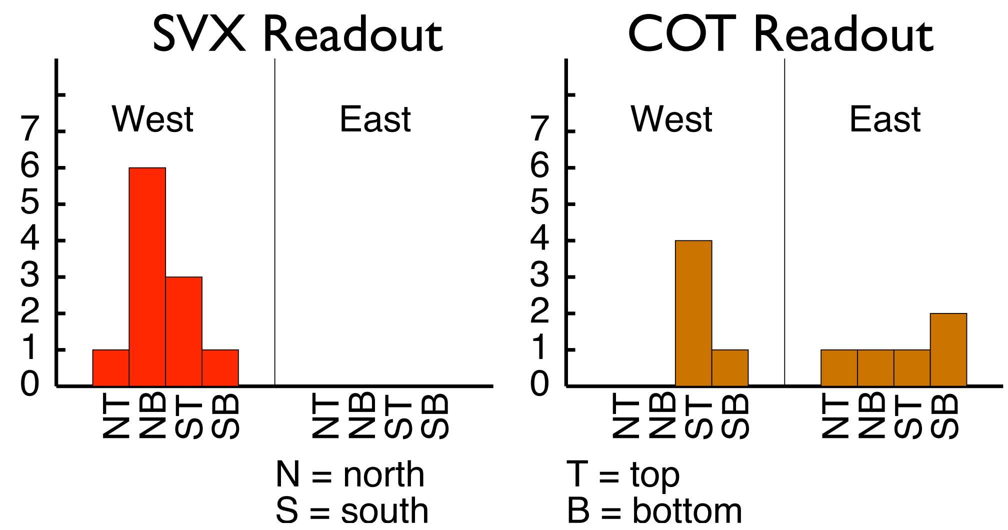
http://www-cdfonline.fnal.gov/ops/acnet/ACNET_beamquality.html

CDF VME Power Supply Failures

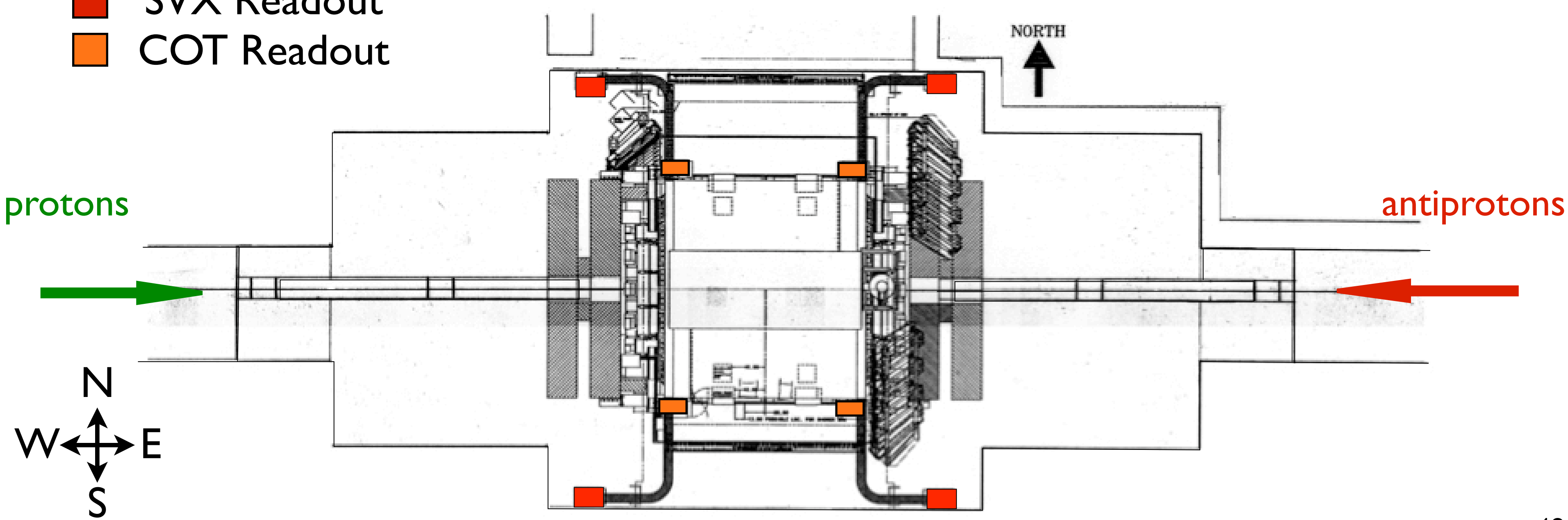
Failure Characteristics

- Position Dependent
- Beam Related
- Catastrophic
- Switching supplies only
- failure rate ~3/week
- 12 supplies failed in 1 day

Failure Locations



SVX Readout
COT Readout

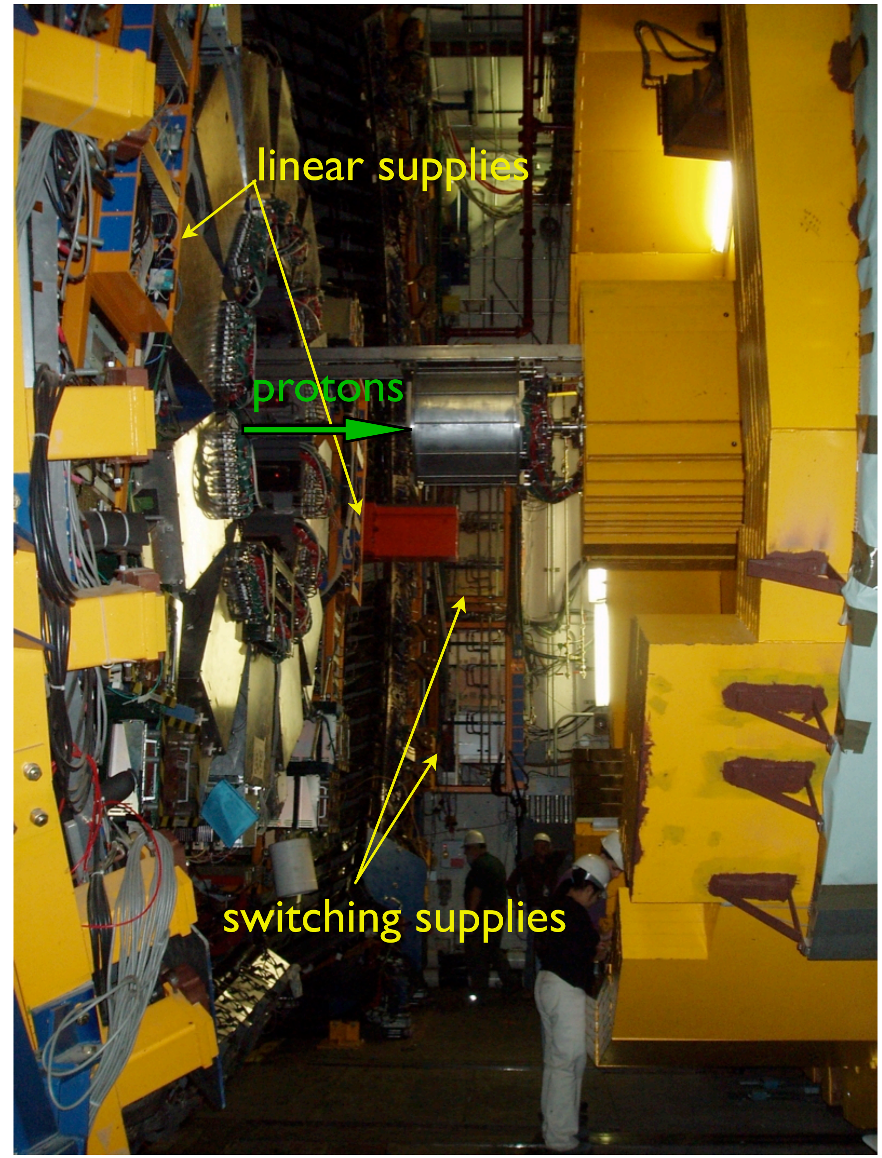


St Catherine’s Day Massacre

12 switching power supplies failed in an 8 hour period.

- only during beam
- only switching supplies
- failures on detector east side
- shielding moved out
- new detector installed
- beam pipe misaligned

Conclusion: Albedo radiation from new detector

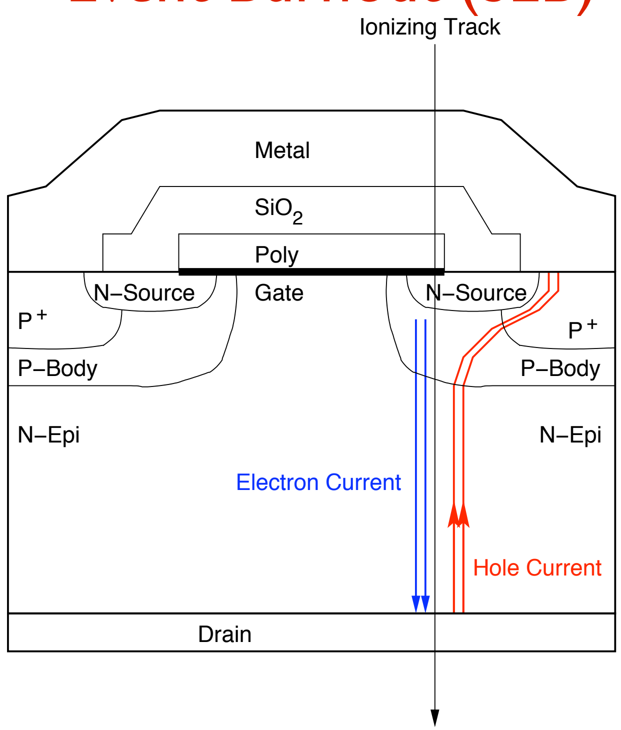


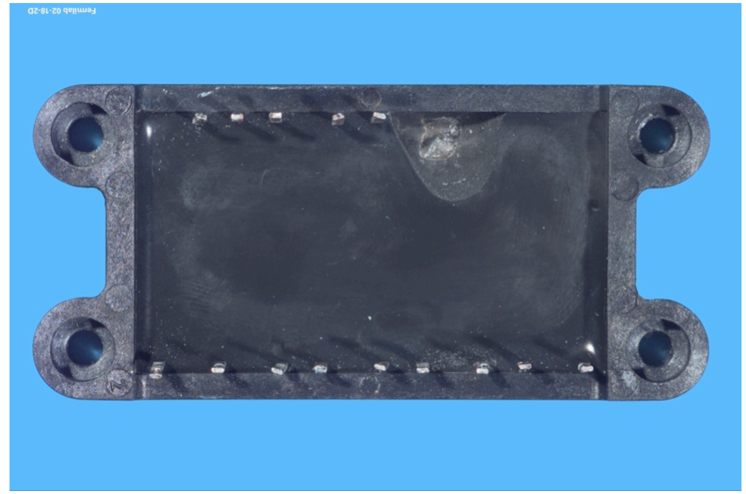
L.V. Power Supply Failures

Power Factor Corrector Circuit

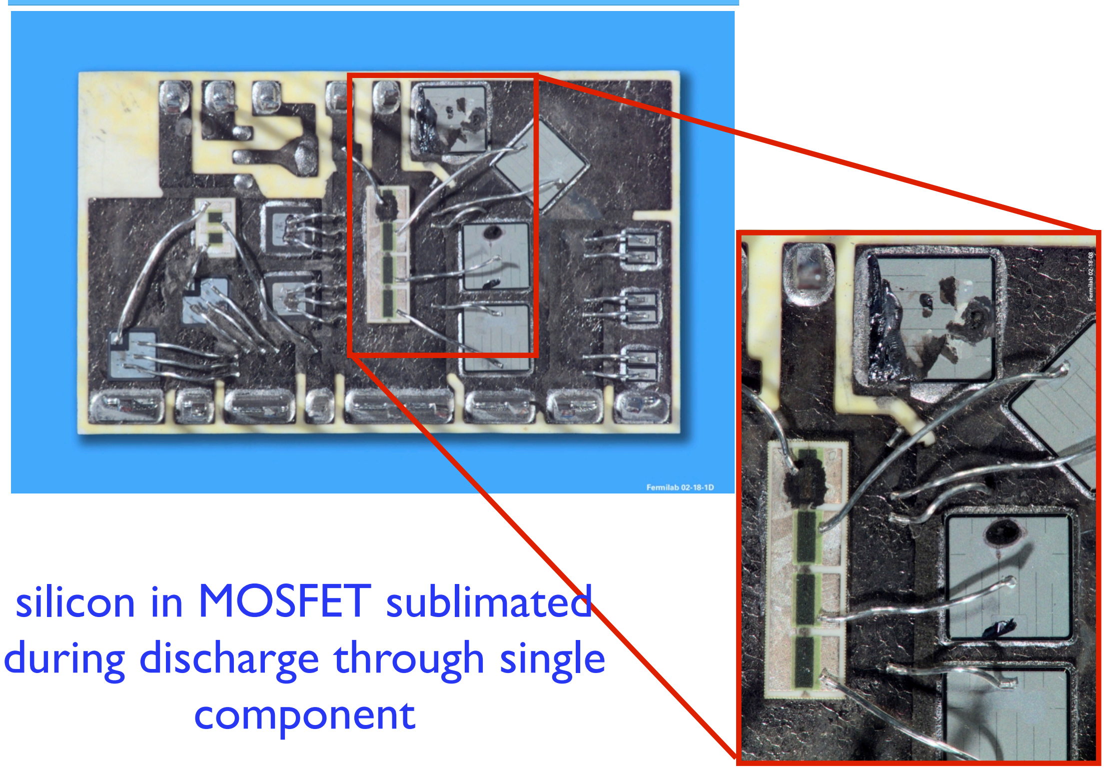
Most failures were associated with high beam losses or misaligned beam pipe

> Power MOSFET Single Event Burnout (SEB)





epoxy covering fractured



silicon in MOSFET sublimated during discharge through single component

Modeling the ionizing radiation field

a) Losses are not negligible, even in the $\bar{p}$ side

b) Shielding on the p side has reduced dose rates by $\sim 25\%$

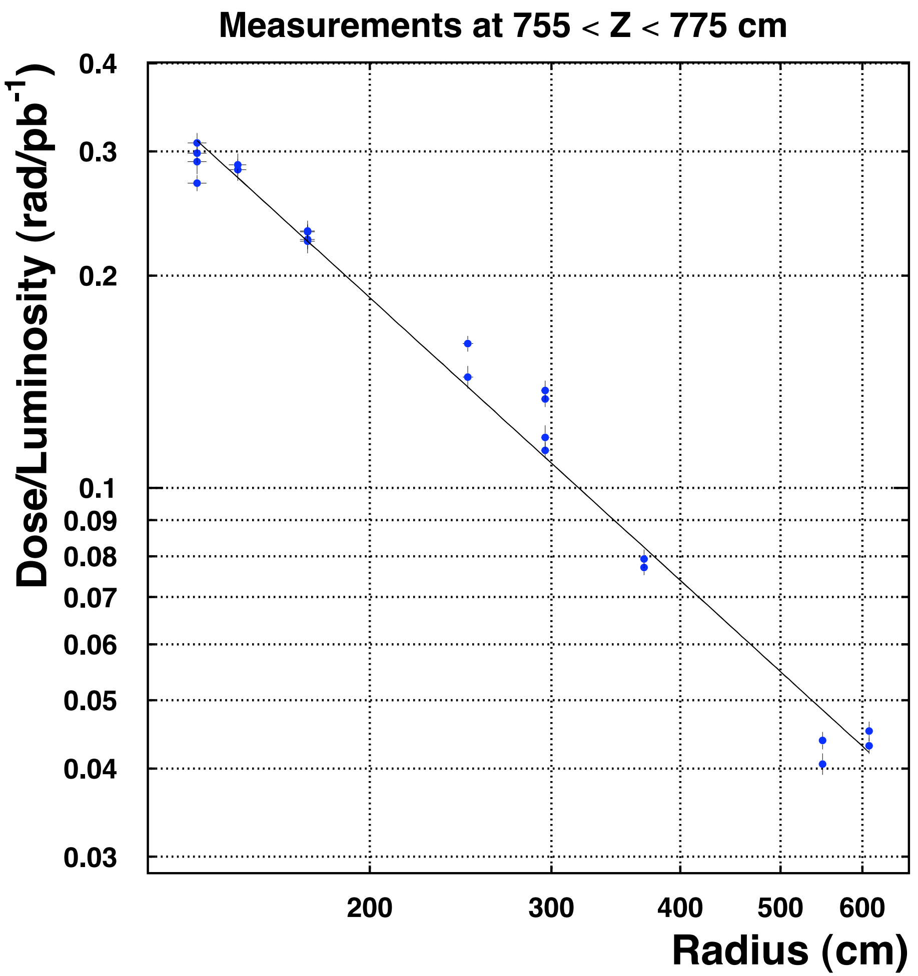
c) No separation of loss/collision contribution point-by-point

$\Rightarrow$ construct total radiation field.

Simple model (D. Amidei et al.: NIM **A320** (1994) 73)

- Cylindrical symmetry about the beam
- Field follows power law in $1/r$ (r = distance from beam)

$$\boxed{\text{Dose}(r) = A r^{-\alpha}}$$

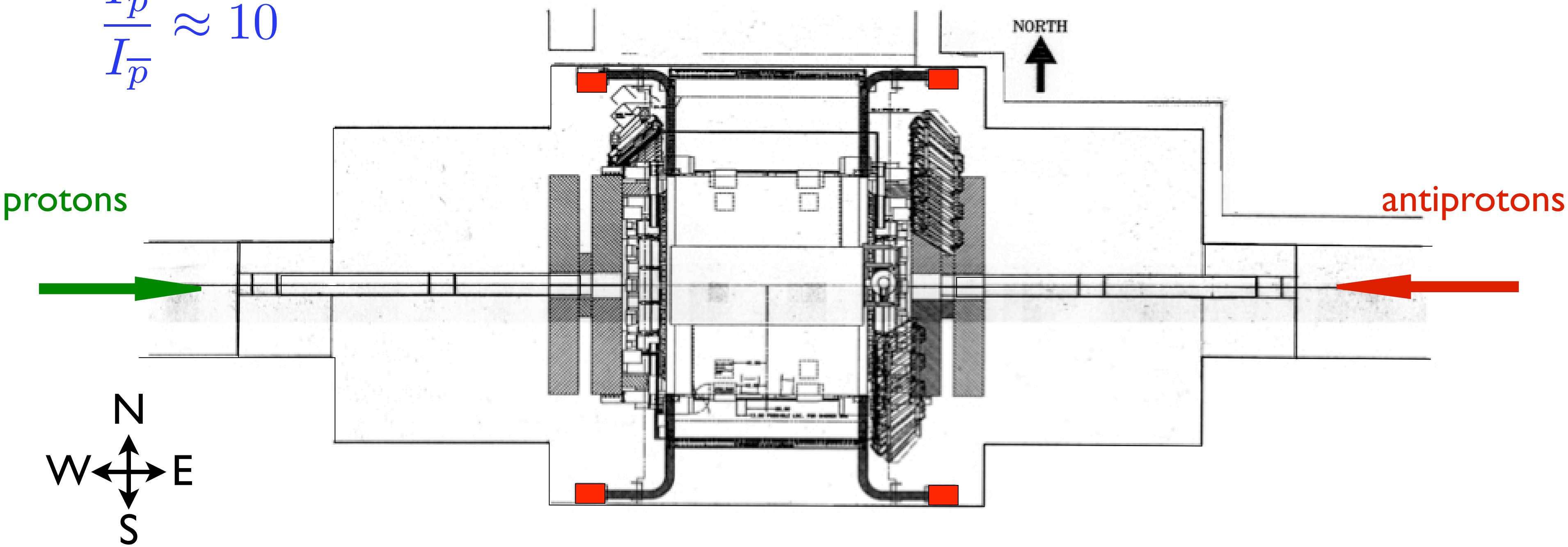


Radiation Source?

- Counter measurements show low beta quadrupoles form a line source of charged particles.
- Power supply failure analysis shows largest problem on the west (proton) side of the collision hall.

CDF Detector (R-rated)

$$\frac{I_p}{I_{\bar{p}}} \approx 10$$



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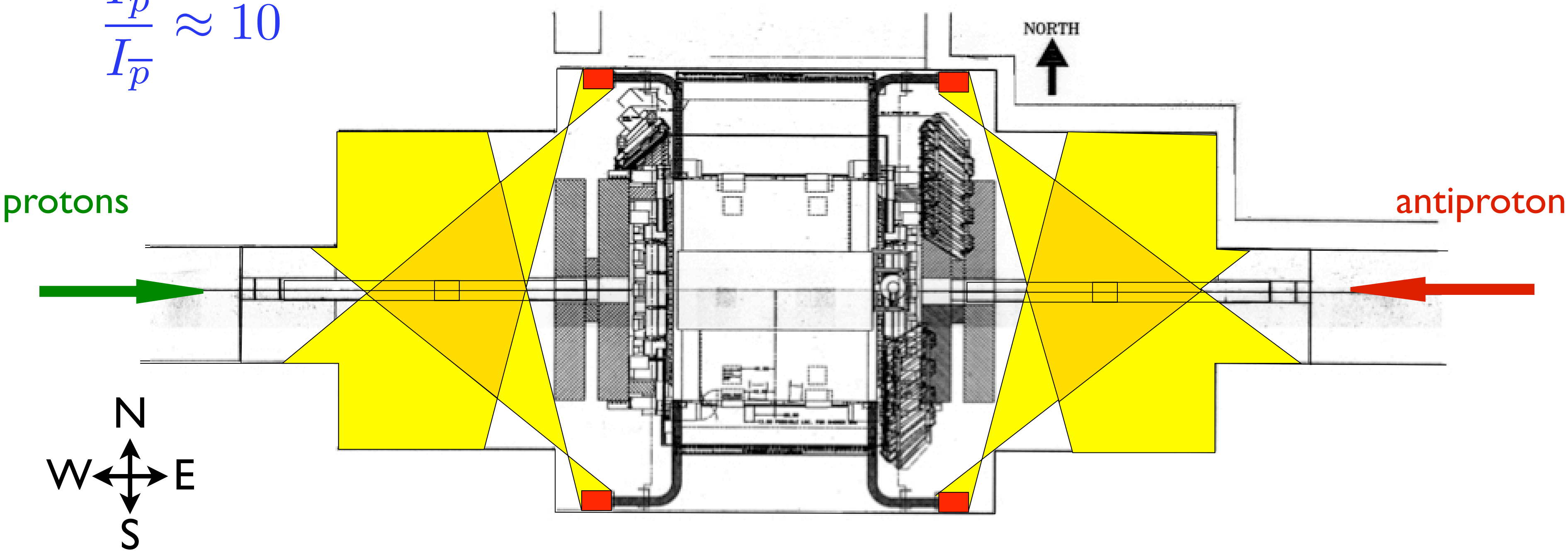
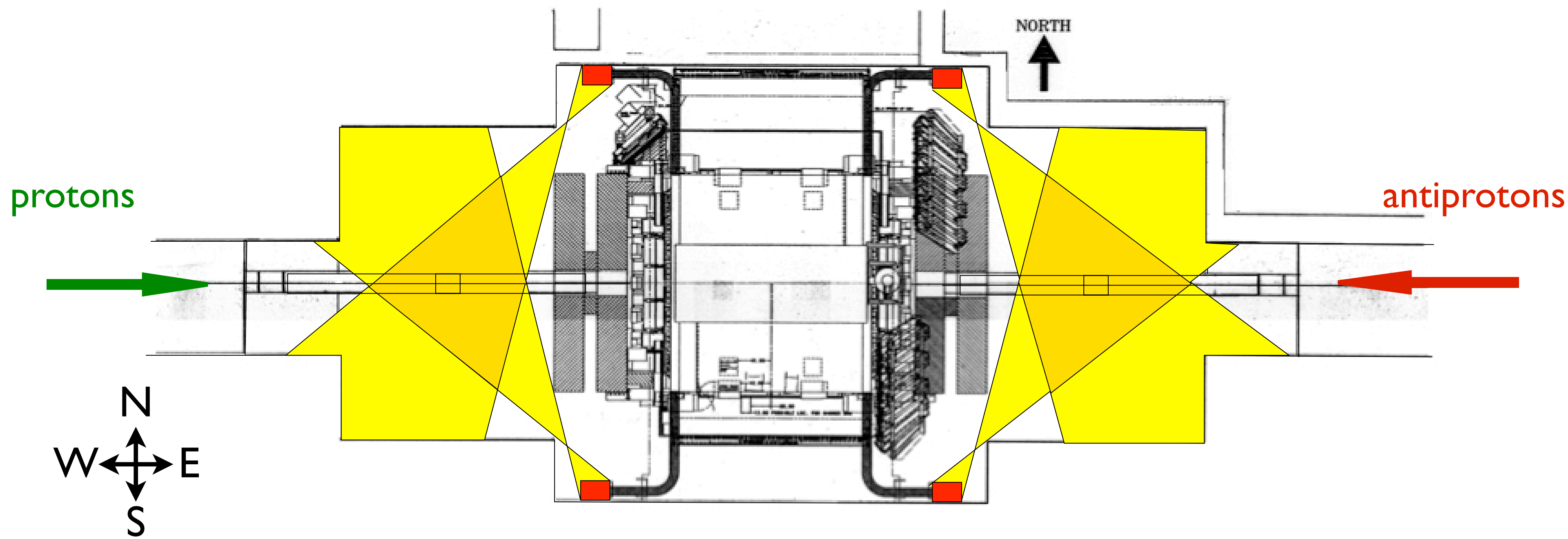


Radiation Shielding?

Install shielding to reduce radiation from low beta quadrupoles.

CDF Detector w/ additional shielding



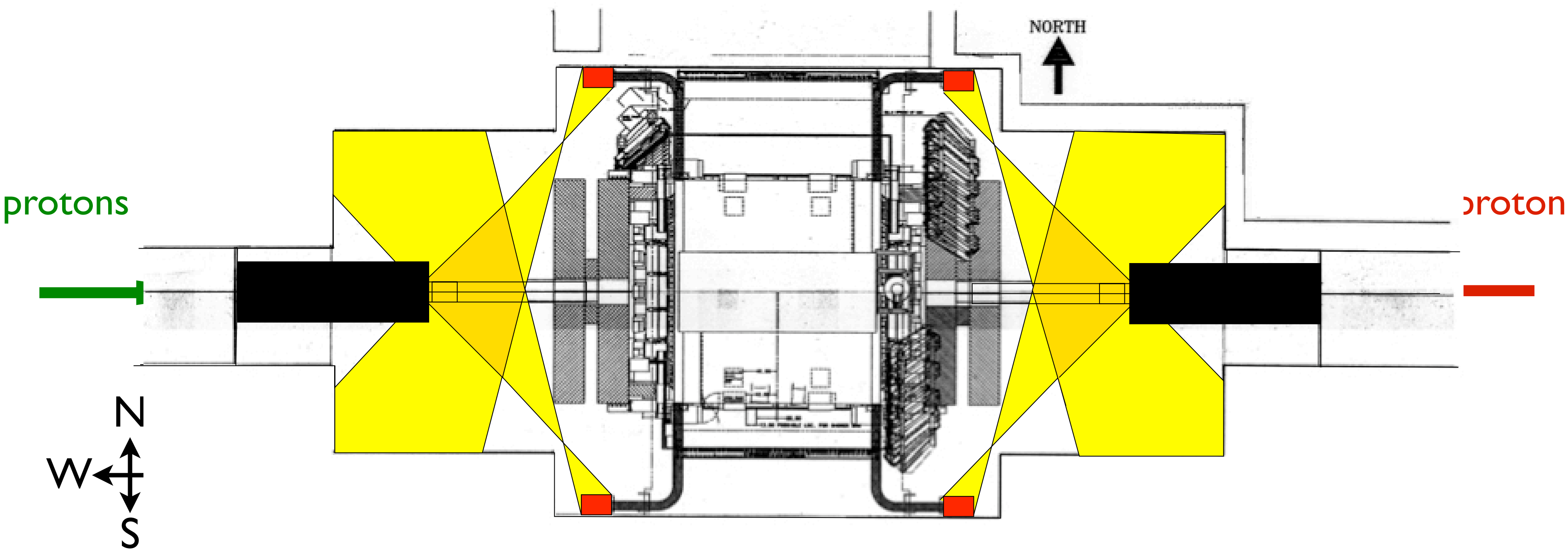
Radiation Shielding?

Install shielding to reduce radiation from low beta quadrupoles.

Reduces solid angle seen by power supplies by 25%

What do measurements tell us?

CDF Detector w/ additional shielding

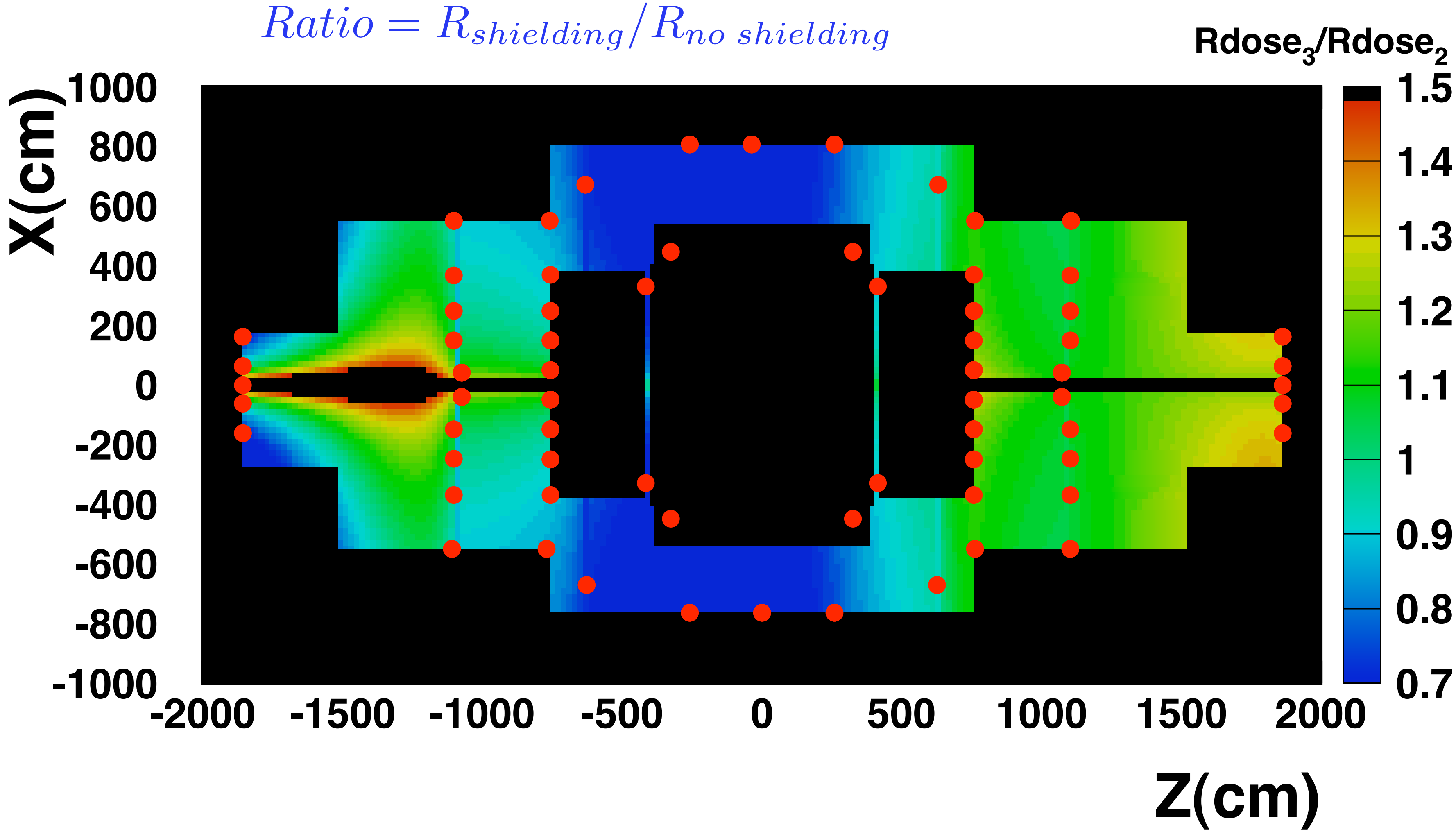


Collision Hall Ionizing Radiation

Shielding effectiveness (west side only)

- Ionizing radiation reduced by 20-30% near affected power supplies
- What about neutrons?

$$Ratio = R_{shielding}/R_{no\ shielding}$$

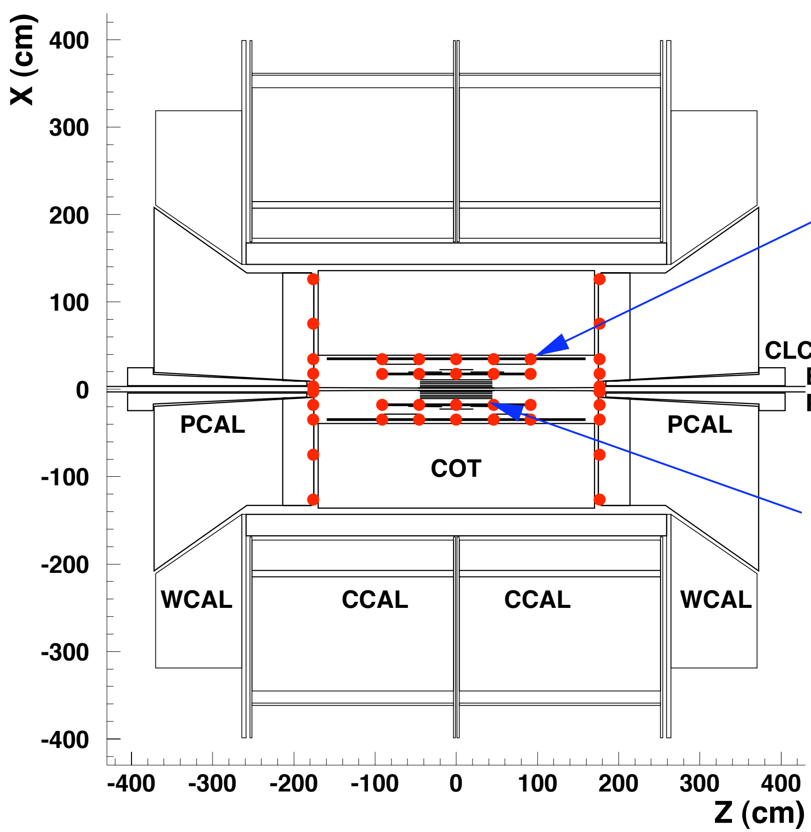


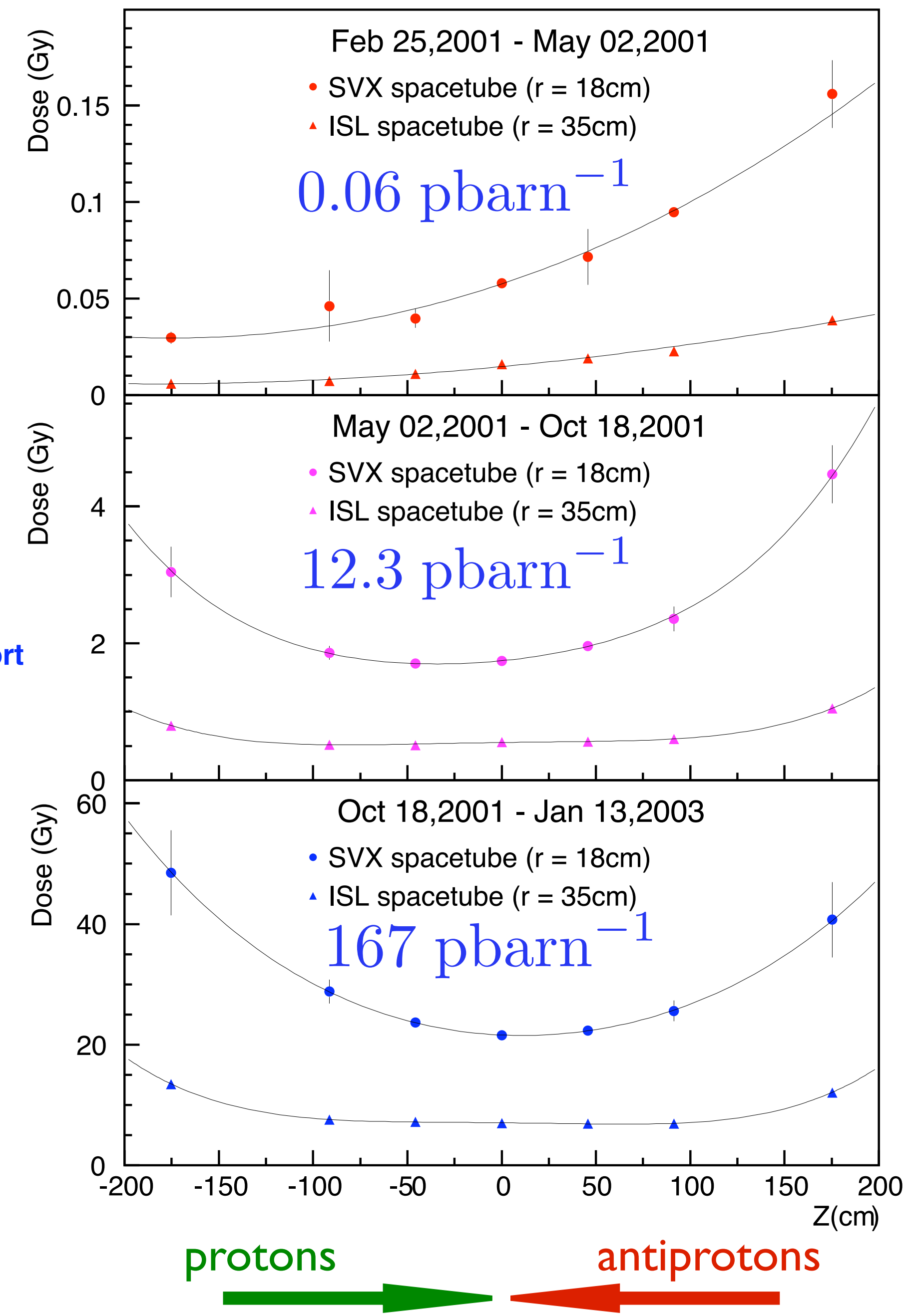
Radiation Measurements

TLDs installed in tracking volume

3 exposure periods

- 0.06 pbarn^{-1} (p-loss dominated)
- 12.3 pbarn^{-1}
- 167 pbarn^{-1}



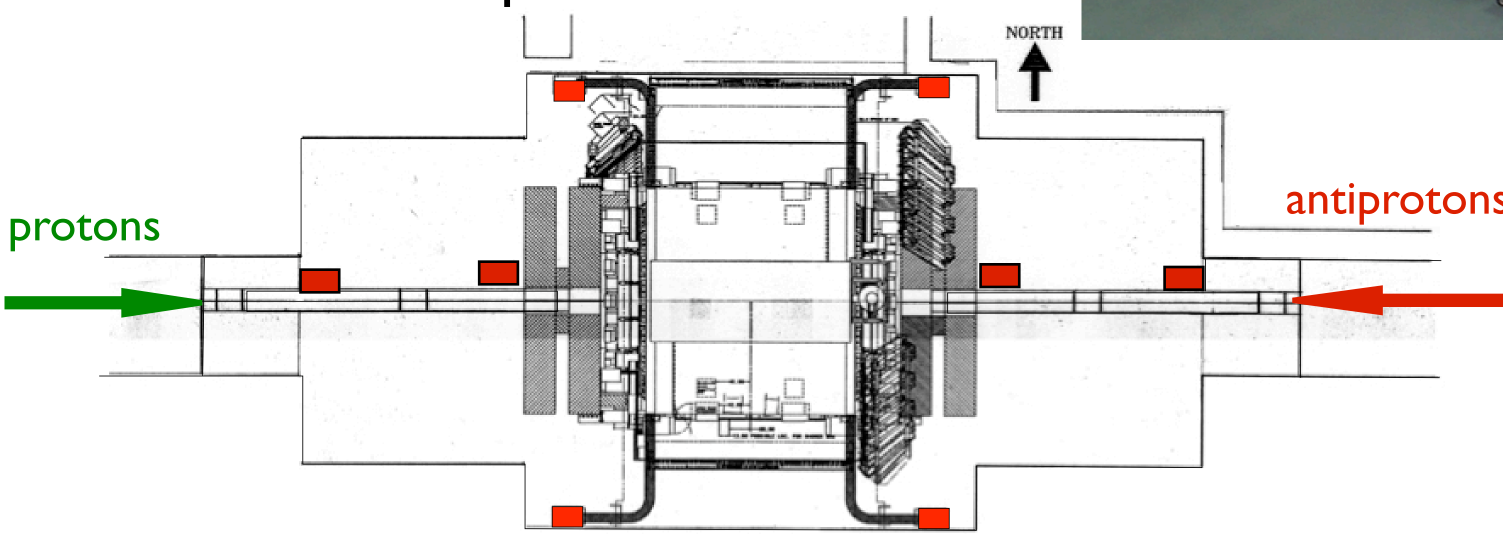


Neutron Spectrum Measurement

- Evaluate Neutron Energy Spectrum
  - Bonner spheres + TLDs
  - ~1 week exposures
  - Shielding in place
- Measuring neutrons is hard
- Work in progress...

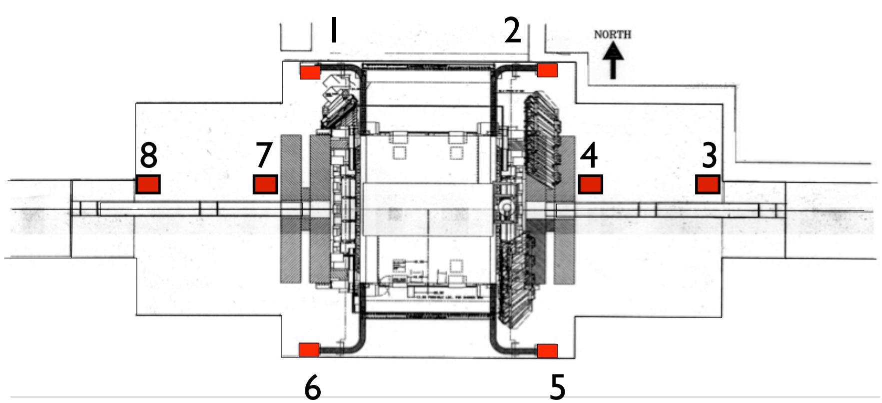
Polyethylene “Bonner” spheres

Bonner sphere locations



Neutron Data

- Compare data with ^{252}Cf
  - spontaneous fission
  - ~20 n/decay
  - $\langle E_n \rangle$ ~2 MeV
- Data show average E_n < 2 MeV
- To do:
  - understand E_n distribution
  - neutron fluence



W. Schmitt, *et al.*